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Invited Review

Some things we can infer about the Moon from the composition of the Apollo 16 regolith

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Abstract–Characteristics of the regolith of Cayley plains as sampled at the Apollo 16 lunar landing site are reviewed and new compositional data are presented for samples of <1 mm fines ("soils") and 1–2 mm regolith particles. As a means of determining which of the many primary (igneous) and secondary (crystalline breccias) lithologic components that have been identified in the soil are volumetrically important and providing an estimate of their relative abundances, more than 3×10^6 combinations of components representing nearly every lithology that has been observed in the Apollo 16 regolith were systematically tested to determine which combinations best account for the composition of the soils. Conclusions drawn from the modeling include the following. At the site, mature soil from the Cayley plains consists of 64.5% ± 2.7% components representing "prebasin" materials: anorthosites, feldspathic breccias, and a small amount (2.6% ± 1.5% of total soil) of nonmare, mafic plutonic rocks, mostly gabbronorites. On average, these components are highly feldspathic, with average concentrations of 31–32% Al_2O_3 and 2–3% FeO and a molar Mg/(Mg + Fe) ratio of 0.68. The remaining 36% of the regolith is syn- and postbasin material: 28.8% ± 2.4% mafic impact-melt breccias (MIMBs, *i.e.*, "LKFM" and "VHA basalts") created at the time of basin formation, 6.0% ± 1.4% mare-derived material (impact and volcanic glass, crystalline basalt) with an average TiO_2 concentration of 2.4%, and 1% postbasin meteoritic material. The MIMBs are the principal (80–90%) carrier of incompatible trace elements (rare earths, Th, *etc.*) and the carrier of about one-half of the siderophile elements and elements associated with mafic mineral phases (Fe, Mg, Mn, Cr, Sc). Most (71%) of the Fe in the present regolith derives from syn- and postbasin sources (MIMBs, mare-derived material, and meteorites). Thus, although the bulk composition of the Apollo 16 regolith is nominally that of noritic anorthosite, the noritic part (the MIMBs) and the anorthositic part (the prebasin components) are largely unrelated. There is compositional evidence that 3–4% of the soil is Th-rich material such as that occurring at the Apollo 14 site, and one fragment of this type was found among the small regolith particles studied here. If regolith such as that represented by the Apollo 16 ancient regolith breccias was a protolith of the present regolith, such regolith cannot exceed ~71% of the present regolith; the rest must be material added or redistributed since closure of the ancient regolith breccias. The postclosure material includes the mare-derived material and the Apollo-14-like component.

Compositions of all mature surface soils from Apollo 16, even those collected 4 km apart on the Cayley plains, are very similar, which is in stark contrast to the wide compositional range of the lithologies of which the soil is composed. This uniformity indicates that the ratio of MIMBs to feldspathic prebasin components is not highly variable in the megaregolith over distances of a few kilometers, that there are no large, subsurface concentrations of "pure" mafic impact-melt breccia, and that the intimate mixing is inherent to the Cayley plains at a gross scale. Thus, the mixing of mafic impact-melt breccias and feldspathic prebasin components must have occurred during formation and deposition of the Cayley plains; such uniformity could not have been achieved by small postdeposition impacts into a stratified megaregolith. Using this conclusion as one constraint, and the known distribution of Th on the lunar surface as another, and the assumption that the Imbrium impact is primarily responsible for formation of the Cayley plains, arguments are presented that the Apollo 16 MIMBs derive from the Imbrium region, and, consequently, that one-fourth of the Apollo 16 regolith is primary Imbrium ejecta in the form of mafic impact-melt breccias.

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There is no dark side of the Moon, really; matter of fact it's all dark.
Roger Waters (1973)

INTRODUCTION

The Apollo 16 mission to the Moon is the only manned mission to have obtained samples from a region expected to be reasonably typical of the ancient, heavily-cratered highlands crust. The site is ~300 km from the nearest mare basin, Mare Tranquillitatis (Hodges, 1981) but at the interface between two landforms identified photogeologically in premission planning to be characteristic of the Central Highlands. To the east and south is the hummocky terrain of the Descartes Mountains; to the west and north are regions of smooth, low-lying plains of the Cayley Formation (Fig. 1). A primary goal of the mission was to obtain samples from the two units in order to determine their derivation.

The origins of the Cayley and Descartes Formations have been the topic of much discussion, both pre and postmission (Hodges and Muehlberger, 1981; Hörz *et al.*, 1981; Spudis, 1984; Wilhelms, 1987). Prior to the Apollo 16 mission, the Cayley plains were expected to be volcanic flows or pyroclastic deposits because of their flatness and ponded character (Muehlberger *et al.*, 1980; Hodges, 1981). Although the Apollo 16 LM (lunar module) landed on the Cayley plains, no volcanic rocks were found. Instead, most of the rocks were impact-melt breccias that were considerably more mafic than the regolith fines (in this respect, the site is probably atypical of vast areas of the highlands). Thus, most postmission work has attributed both landforms to basin-forming impacts. Recent works usually interpret the Descartes Formation as an ejecta deposit from the Nectaris basin to the east of the site, probably modified by Imbrium, and the Cayley plains are thought to be a continuous deposit (a mixture of primary ejecta and local material) from the Imbrium basin to the northwest, possibly modified by the Orientale impact (Hörz *et al.*, 1981; Spudis, 1984; Wilhelms, 1987). A point of unresolved contention has been the relative proportions of pre-Nectaris material, Nectaris ejecta, and primary Imbrium ejecta at the site. Material from the Imbrium region should dominate the Cayley Formation if the Cayley plains were emplaced largely as primary Imbrium ejecta, as has been advocated by Wilhelms (1981). Nectaris ejecta and pre-Nectaris material should dominate if primary Imbrium ejecta are a minor component and the local materials were largely reworked by mixing and lateral transport during emplacement of the Cayley plains (Morrison and Oberbeck, 1975; Head and Hawke, 1981; Hörz *et al.*, 1983). Samples have provided only an ambiguous constraint because it is not known whether a given rock is of local derivation or was ejected from the Imbrium or Nectaris cavity. Thus, despite more than 25 years of sample study, "the relative amounts of Imbrium and Nectaris ejecta in the Descartes and Cayley Formations are unknown" (Wilhelms, 1987). Resolution of these questions is important for understanding how material is redistributed in basin-forming impacts.

Interpretations of the site geology have been based primarily on photogeology, models for distribution of basin ejecta, studies of terrestrial craters, and petrologic and geochemical studies of the rock samples. In this work, I consider constraints imposed by regolith composition. In large part, the work is a review that focuses on the relationship between composition and geology. In this portion of the work, I emphasize certain issues that I perceive to be sometimes misunderstood about the Apollo 16 regolith and discuss in consistent terminology other issues that may be difficult for the newcomer to follow through 25 years of evolving literature (highland rock nomenclature, melt-breccia groups, the Cayley-Descartes dichotomy). In addition, the work provides a new mass-balance model for the composition of the regolith of the Cayley plains with the goals of (1) identifying the relative contributions of Imbrium and Nectaris ejecta, (2) determining the relative abundances of rock types, and (3) determining how the chemical elements are distributed among the various chemical components of the regolith. The paper relies largely on compositional data obtained in this laboratory by instrumental neutron activation analysis (INAA) on more than 1300 samples from the Apollo 16 regolith, not all of which have been previously published. New compositional data are presented for samples of <1 mm fines ("soils") and individual particles from the 1–2 mm grain-size fraction of several regolith samples from the Cayley plains at Apollo 16.

SOME CONCEPTS AND BACKGROUND

In this section, I review some concepts and background that are useful when considering the composition of the Apollo 16 regolith.

The Cayley-Descartes Dichotomy at the Apollo 16 Site

The Apollo 16 mission was designed so that stations 1 and 2 (Fig. 2) would yield samples typical of the Cayley plains (Muehlberger *et al.*, 1980; Muelhberger, 1981). Data from the Apollo orbiting gamma-ray experiments confirm that the moderately high Th concentrations (2–3 μg/g) of the soils of stations 1 and 2 are typical of the Cayley plains regionally (Fig. 3). In premission planning, it was anticipated that Descartes material would be found on Stone Mountain at station 4 at the southern extreme of the traverses. Postmission sample studies, however, have shown that soil compositions at station 4 and the other southern stations (5, 6, 8, and 9) are not feldspathic and Th poor, as expected for the Descartes Formation or Kant Plateau to the east of the site based on orbital geochemical data (Fig. 3; Andre and El-Baz, 1981) but instead are very similar to those of the central stations (1, 2, and the LM station). Even the 0.6 m core taken on Stone Mountain at station 4 contains soil throughout its length that is compositionally similar to soil of the Cayley plains at the central stations (Korotev *et al.*, 1984; Korotev and Morris, 1993). Rock types found at station 4 are also essentially similar to those of the central area (Delano *et al.*, 1973; Ryder, 1981). Thus, if the surface material at stations 1 and 2 is representative of the Cayley plains, material of the Cayley plains also dominates at the surface of station 4 and other southern stations, although the Cayley material may overlie Descartes material.

Feldspathic, Th-poor material such as that expected from the Descartes Formation dominates the ejecta of North Ray Crater at station 11 (~1 km diameter; Fig. 2). It is likely that the best samples of the Descartes Formation were obtained at station 11 because the North Ray impactor was able to penetrate the surficial Cayley deposit (70–220 m; Cooper *et al.*, 1974) and eject underlying Descartes material (Stöffler *et al.*, 1985). It is useful to keep the Cayley-Descartes dichotomy in mind when considering "the Apollo 16 regolith," as the two regoliths have a different histories, lithologies, and compositions (Stöffler *et al.*, 1985; Wilhelms, 1987; Korotev, 1981, 1996). Regionally, surface materials at the Apollo 16 site are largely materials of the Cayley Formation, which is an important consideration when relating the Apollo 16 samples to remotely obtained data for the region.

Mature Surface Soil of the Cayley Plains

About 42 samples of fines were collected at the surface and from trenches (up to 30 cm deep) using scoops during the Apollo 16 mission. These samples have 6xxx0 (unsieved) or 6xxx1 (<1 mm) sample numbers and are collectively designated "surface" soils in this paper to distinguish them from samples collected with coring equipment. The term "soil" usually refers to <1 mm fines.

A useful reference suite is the subset of mature surface soils (Table 1). "Mature" refers to soil with a high degree of surface exposure, that is, soil that has undergone extensive bombardment by micrometeorites and irradiation by solar and cosmic charged particles (McKay *et al.*, 1991). Mature soils tend to be fine grained and well mixed compared to freshly disaggregated rock. Operationally, mature soils are usually defined as those for which the ferromagnetic resonance parameter I_s/FeO exceeds 60 (Morris, 1978b). Most soil at the

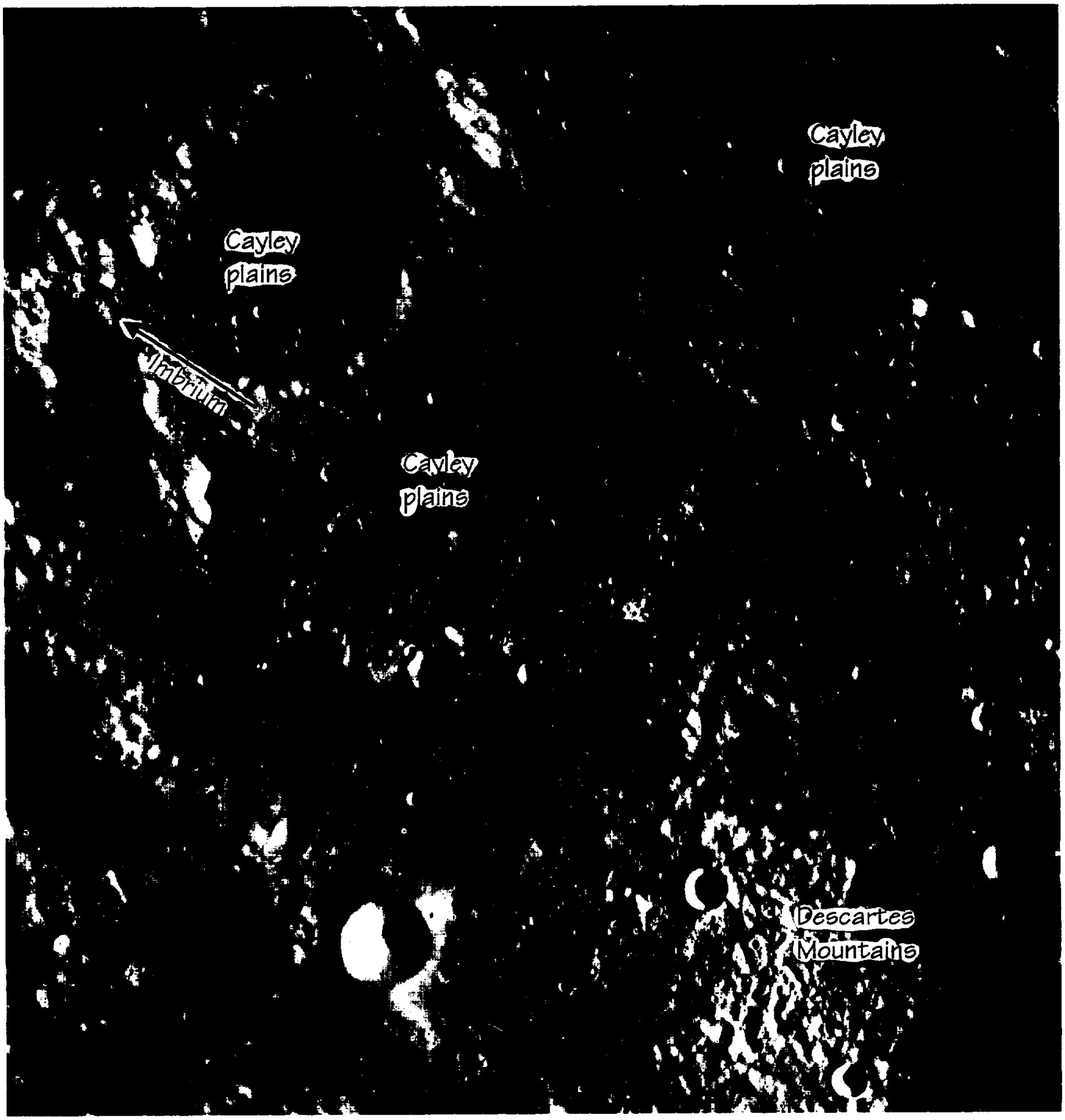

FIG. 1. Mapping camera photo (AS16-M-440) of the Apollo 16 landing site and vicinity. The rectangle approximates the area of the map of Fig. 2. Units of Cayley plains, believed to be continuous ejecta deposits from the Imbrium basin to the northwest, fill low-lying areas (*e.g.*, Wilhelms, 1987). Large craters Dollond C and Dollond B in the upper left corner of the photo are 32 and 37 km in diameter, respectively.

surface of the Cayley plains is mature: of the 36 regolith samples collected at the central and southern stations (including the top 10 cm of five cores), 28 (78%) are mature, 7 (19%) are submature (I_s/ FeO: 30–60), and only one (3%) is immature (I_s/FeO: <30; Morris, 1978b), thus leading to an average I_s/FeO of 78. Regolith maturity generally decreases with depth, although the decrease is irregular. For example, just 60 cm below the surface (the depth reached by the double drive tubes), I_s/FeO averages 52 (range: 34–73; based on double drive tubes 60009/10, 60013/14, 64001/2, and 68001/2; Morris and Gose, 1976; Korotev and Morris, 1993; Korotev *et al.*, 1984; 1997b).

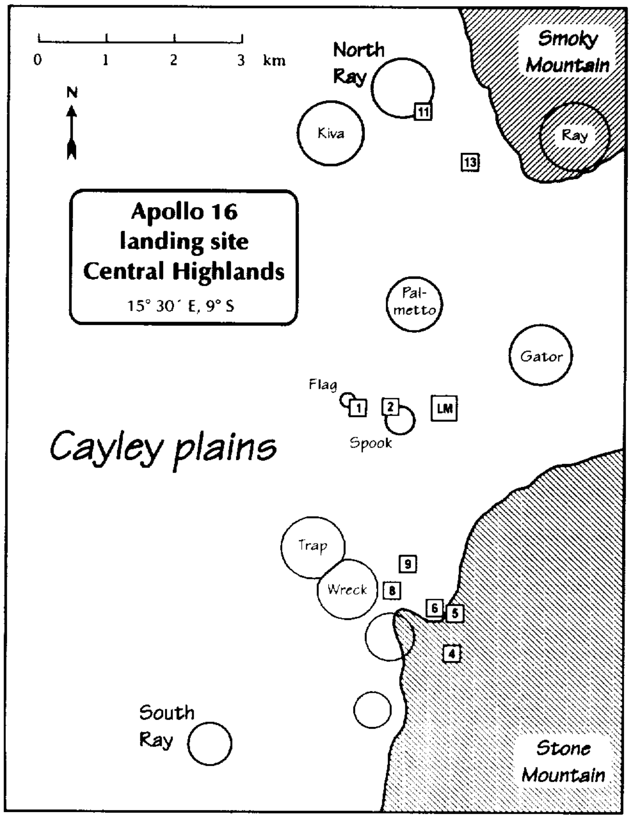

FIG. 2. Schematic map of the Apollo 16 landing site (after Fig. 5 of Muehlberger, 1981). LM (lunar module) marks the landing site and the other squares represent sampling stations. North and South Ray Craters are recent craters with fresh ejecta deposits.

Impacts large enough to penetrate the regolith, which is ~12 m thick at the site (Cooper *et al.*, 1974), eject onto the surface material that has had little or no previous surface exposure. Subsequent smaller impacts mix this fresh material with the previous surface regolith, thus resulting in surface material with a lower average maturity. With time, regolith matures as the freshly uncovered material is irradiated and exposed to micrometeorite impacts (McKay *et al.*, 1974). In contrast to the maturity of soil from recently undisturbed areas of the Cayley plains, none of the soils collected at stations 11 and 13 near North Ray Crater is mature because the 40–50 million years that have elapsed since the crater formed (Borchardt *et al.*, 1986) are an insufficient amount of time (Morris, 1978a) to produce mature regolith from the previously unexposed rock fragments excavated from the crater. Immature material may prevail at depths much shallower than the thickness of the regolith. For example, the single immature soil from the central and southern stations, sample 61221 (I_s/FeO = 9), was collected on the rim of Plum crater, which is only ~30 m in diameter and, thus, represents a maximum excavation depth of only ~3 m (Melosh, 1989).

The significance of mature soil is that it is likely to represent a better average of the upper few meters of regolith than any less mature soil that might occur in the same vicinity. At Apollo 16, samples of mature surface soil (as well as mature soil at depth in cores) are all very similar in composition while all of the compositionally extreme soils are less mature (Fig. 4). The compositional similarity of the mature surface soils extends to at least 10 cm depth as the top 10 cm of the five cores that have been studied all have nearly identical compositions (Fig. 4) even though the cores from stations 4 and 8 were collected 3–4 km south of the three cores from the LM area (Fig. 2). The small range of compositions exhibited by the mature soils is striking in contrast to the wide range of compositions seen among the lithologic components of the soil (Fig. 5) and among the immature soils from the rim of North Ray Crater (Korotev, 1996). A first-order conclusion of this comparison, one emphasized again below, is that the various lithologic components of the soil of the Cayley plains (at the Apollo 16 site, at least) occur in nearly constant

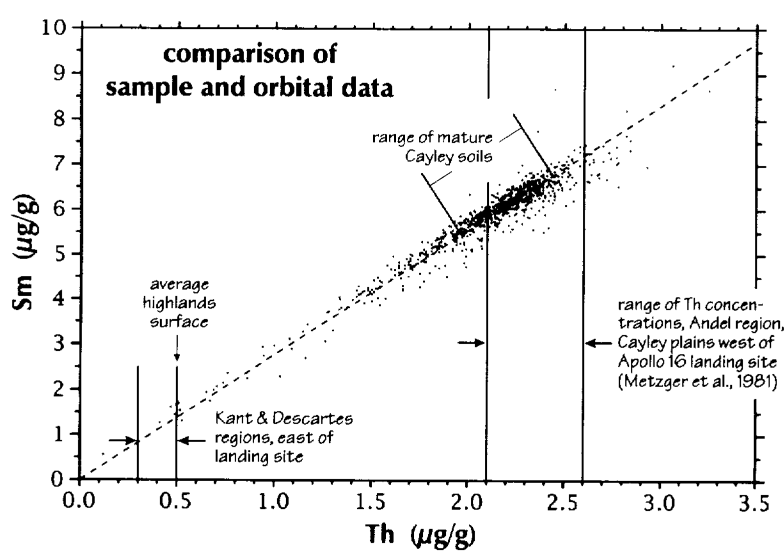

FIG. 3. Variation of Sm and Th concentrations in Apollo 16 soils (surface and cores) and comparison to results of the orbiting gamma-ray experiments for the surface concentration of Th in the Central Highlands (Metzger *et al.*, 1981). Concentrations of the two elements are highly correlated in the soils (R^2 = 0.932, N = 928; some anomalous samples plotting outside the bounds of the figure are excluded) because mafic impact-melt breccias are the only high-Th, high-Sm components of the regolith (Th: 4–9 μg/g) and the Sm/Th ratio of the melt breccias is essentially constant (Table 2). The dotted diagonal line represents the average Sm/Th ratio of the soils (2.77). The long vertical lines indicates the range of Th concentrations for the Andel data region, which represents the Cayley plains west and north of the landing site (Fig. 1). The plot shows that the range of Th concentrations in mature soils from Apollo 16 strongly overlaps that of the surface of the Cayley plains. Because of strong interelement correlations among Apollo 16 soils (*e.g.*, Fig. 7), concentrations of other elements are probably similar as well and we can reasonably conclude that mature Apollo 16 soils (*i.e.*, most surface soils from the central and southern stations) are typical of the local Cayley plains. Most of the soil samples with <1 μg/g Th are from station 11 at North Ray Crater (Korotev, 1996); only these are similar to the Kant and Descartes regions east of the landing site.

proportions and those proportions are not strongly affected by sample location. The station-to-station similarity in soil compositions at the Apollo 16 site contrasts with the large range observed at the Apollos 15 and 17 sites (*cf.*, Figs. 4 and 6). All Apollo 14 soil compositions are also similar to each other (Fig. 6); however, most of the rocks of which the Apollo 14 soil is composed are much more similar in composition to the soil (Jolliff *et al.*, 1991a) than they are at Apollo 16.

For the rest of this paper, "mature Cayley soil" refers generically to mature soil such as that found at the surface of the site and "MCS" refers specifically to a model component with the average composition of mature surface soils from the central and southern stations (Table 2).

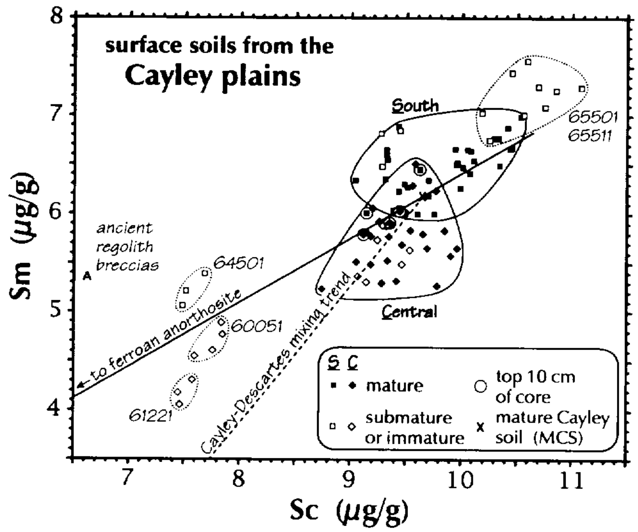

FIG. 4. Variation of Sm and Sc concentrations in surface and trench soils (<1 mm fines, samples 6xxx1) from the Cayley plains. The data are keyed according to surface maturity (Morris, 1978b) and location: south (S) = stations 4, 5, 6, 8, and 9 and central (C) = stations LM(10), 1, and 2. Each point represents a single analysis and two or more points are plotted for each sample. Circled points represent the mean of the ~20 samples (all mature) from the top 10 cm of each of the drive tubes and cores that have been processed. Compositionally anomalous samples are always submature or immature (open symbols) and only the submature soils from station 5 (65501 and 65511) are more mafic than the mature soils. Mature soils are richer in Sc than the ancient regolith breccias (symbol A; mean from Korotev, 1996) because the soils contain mare-derived material and the regolith breccias do not (*e.g.*, McKay *et al.*, 1986; Korotev, 1996). The diagonal short-dashed line (Cayley-Descartes mixing trend) connects the average composition of the mature Cayley soils (MCS) with the average composition of soils from North Ray Crater (see also Fig. 10). The solid diagonal line represents addition (or subtraction) of ferroan anorthosite (the FAn component of the model; Table 2) to (or from) the MCS composition; it is essentially the same as the trend defined by samples from the 60009/10 core (Korotev, 1991a). Sources of data: this work, Korotev (1982, 1991a), Korotev and Morris (1993), Korotev *et al.* (1984, 1997b), and McKay *et al.* (1986).

TABLE 1. Mean concentrations of selected elements in mature surface soils from each of the sampling stations of the Cayley plains at the Apollo 16 site and some submature and immature surface soils of unusual composition.

	Mature									Submature and Immature			
	stn. LM	stn. 1	stn. 2	stn. 4	stn. 5	stn. 6	stn. 8	stn. 9	mean	60051	61221	64501	655x1
SiO_2	45.3	44.6	44.5	45.0	45.2	45.2	44.9	45.2	45.0	44.8	45.6	45.2	45.5
TiO_2	0.58	0.60	0.61	0.54	0.63	0.65	0.55	0.61	0.595	0.44	0.50	0.50	0.66
Al_2O_3	26.5	26.5	26.8	27.6	26.5	26.5	26.7	26.3	26.7	28.2	28.3	27.5	25.4
FeO	5.41	5.28	5.35	4.99	5.81	5.78	5.80	5.60	5.51	4.47	4.28	4.61	5.94
MgO	6.24	6.03	6.16	5.50	6.14	6.44	6.26	6.32	6.14	5.3	4.97	4.9	6.72
CaO	15.4	15.4	15.2	15.6	15.2	15.2	15.2	15.1	15.3	15.9	16.0	16.4	14.5
Na_2O	0.451	0.475	0.458	0.451	0.457	0.459	0.453	0.453	0.457	0.457	0.513	0.456	0.477
K_2O	0.12	0.11	0.11	0.12	0.13	0.11	0.13	0.12	0.12	0.12	0.09	0.11	0.14
Sc	9.45	9.35	9.62	9.09	10.29	10.18	9.34	9.83	9.64	7.75	7.49	7.56	10.59
Cr	770	753	766	715	807	802	789	795	775	615	572	589	848
Co	30.2	26.6	27.1	25.5	35.5	36.4	41.1	31.2	31.7	24.7	17.4	35.8	34.4
Ni	432	363	356	353	495	527	639	469	454	342	218	502	484
Sr	182	175	178	178	187	182	186	172	180	188	185	182	172
Zr	189	174	170	186	202	194	195	196	188	150	125	160	218
Cs	0.13	0.14	0.13	0.15	0.15	0.13	0.14	0.15	0.14	0.11	0.10	0.11	0.17
Ba	146	139	138	137	154	150	152	153	146	110	105	125	169
La	13.3	12.2	11.7	12.9	14.5	14.1	14.0	13.8	13.3	10.0	8.9	11.2	15.4
Ce	33.5	32.1	31.1	33.7	38.1	36.6	36.6	35.8	34.7	26.6	23.3	29.3	40.7
Nd	21	19	19	20	23	22	22	21	21	14	14	19	24
Sm	6.14	5.66	5.49	5.98	6.73	6.56	6.49	6.38	6.18	4.70	4.17	5.22	7.19
Eu	1.20	1.19	1.16	1.18	1.22	1.21	1.21	1.22	1.20	1.14	1.21	1.13	1.23
Tb	1.24	1.17	1.13	1.19	1.36	1.31	1.33	1.32	1.26	0.96	0.85	1.06	1.47
Yb	4.31	3.99	3.91	4.26	4.75	4.63	4.54	4.54	4.37	3.31	2.92	3.64	5.13
Lu	0.602	0.560	0.544	0.585	0.661	0.652	0.631	0.626	0.608	0.47	0.41	0.50	0.72
Ir	15.6	12.2	11.8	11.4	17.5	17.3	19.6	15.4	15.1	10.9	5.6	14.7	14.7
Au	8.3	7.0	6.5	12.9	12.4	10.7	13.9	10.2	10.2	7.1	4.2	19.1	9.1
Th	2.23	1.99	2.00	2.18	2.45	2.37	2.29	2.28	2.22	1.73	1.42	1.85	2.65
U	0.57	0.52	0.53	0.57	0.65	0.65	0.60	0.60	0.59	0.46	0.36	0.51	0.71

Oxides in mass percent, others in µg/g, except Ir and Au in ng/g. Mean = mean of preceding columns; 655x1 = mean of samples 65501 and 65511. Data for SiO_2, TiO_2, Al_2O_3, MgO, and K_2O are from the compilation of Korotev (1981); all other data are by INAA (this lab, mostly this work; also Korotev, 1982, 1994; McKay *et al.*, 1986). For the station means, INAA data from 2–6 analyses of each mature (Morris, 1978b) 6xxx1 sample were averaged first, then the means of the 2–4 samples from each station were averaged. See Korotev (1996) for data on soils from North Ray Crater (station 11).

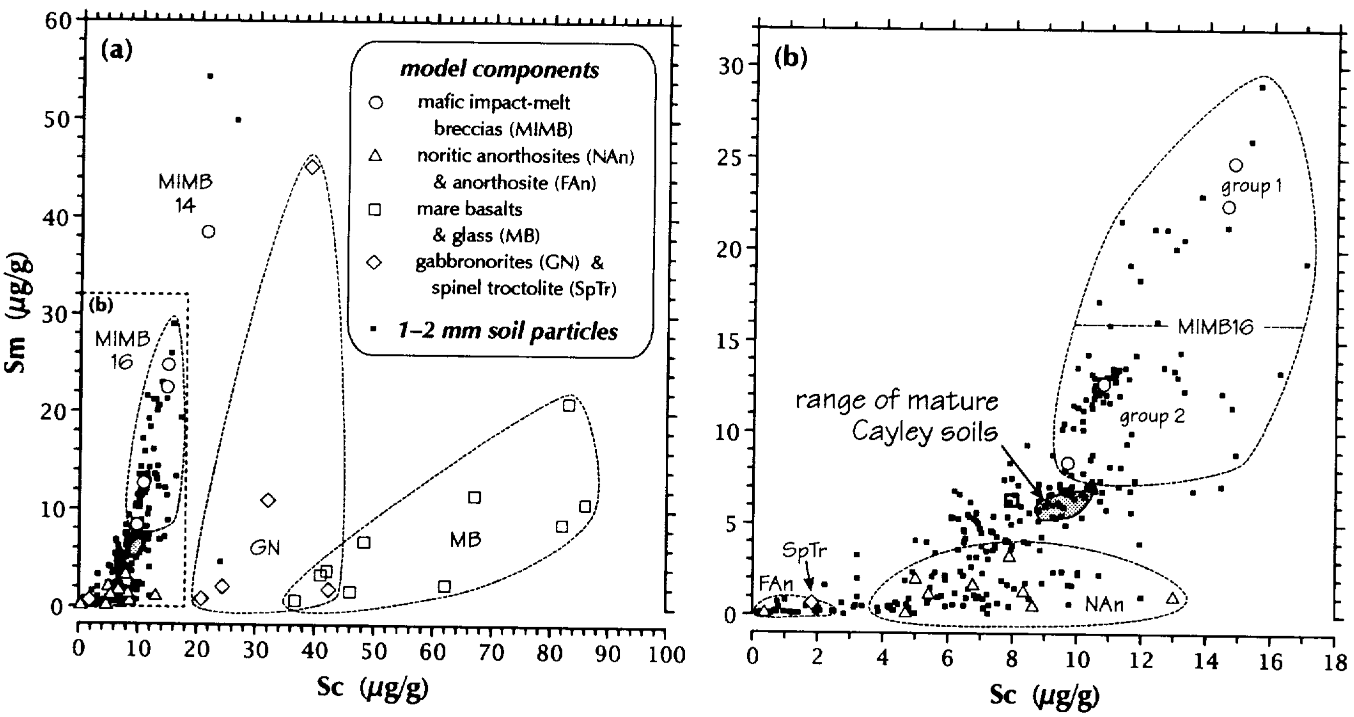

FIG. 5. Concentrations of Sc and Sm in Apollo 16 rocks and comparison to mature Cayley soils. (a) Mare-derived materials and gabbronorites are significantly richer in Sc (*i.e.*, more mafic) than the soils; (b) is an enlargement of the low-Sc area of (a). Each of the components of the mixing models (except the CI-chondrite component) is represented by a large open symbol, and together these components cover the entire range of lithologies found in the Apollo 16 regolith. Also shown are data for a pseudorandom assortment of ~300 particles from the 1–2 mm grain-size fractions of several soils from the Cayley plains; these include particles from cores from the LM area (Korotev, 1991a) and surface soils from stations 4, 5, and 6 (this work; also Haskin *et al.*, 1973). The compositional range of the mature soils is very small compared to the range of the rocks of which the soils are composed, which indicates that the soils are well mixed. The large unfilled square to the left of the soil field represents the average composition of the 1–2 mm particles; the offset in Sc concentration results from the mare-derived component contained in the soils (largely small glass particles) that is not represented among the 1–2 mm particles. The difference in the means (Δ = 1.66 µg/g Sc) is equivalent to ~4% low-Ti mare basalt (50 µg/g Sc). Most of the 1–2 mm particles plotting in or near the soil field are regolith breccias and agglutinates (*i.e.*, rocks constructed from soil). Other particles plotting between the MIMB and NAn fields include glassy melts that are believed to have been produced during formation of South Ray Crater and other feldspathic impact-melt breccias (Morris *et al.*, 1986; Korotev, 1994).

Some Compositional and Mineralogical Considerations

On average, mature Cayley soil contains ~75% normative plagioclase, 17% pyroxenes (primarily orthopyroxene), 6% olivine, 1% ilmenite, and 0.6% $Fe_{94}Ni_6$ metal, by mass. Modally, however, much of the regolith is glass formed from melting of these minerals. From the mineralogical perspective, nearly all of the first-order variation in concentrations of major elements and compatible trace elements among different samples of Apollo 16 soils (and polymict rocks) reflects variation in the ratio of normative plagioclase to mafic minerals; second-order compositional variation is mainly due to variation in the ratio of pyroxene to olivine.

Although differences in the ratio of plagioclase to pyroxene among Apollo 16 soil samples are clearly reflected in the range of Al_2O_3 concentrations, they are even more evident (larger relative difference) in the range of concentrations of elements like Sc that are carried mainly by pyroxene, because pyroxene is in lower abundance than plagioclase. For this and other reasons (Fig. 7), two-element plots using Sc are particularly useful for demonstrating mixing relationships and subtle differences in proportions of components in polymict samples from the lunar highlands (*e.g.*, Korotev *et al.*, 1984; Korotev, 1991a). Iron is also carried by pyroxenes and, like Sc, determined precisely by INAA, but Fe is not a useful measure of bulk composition in small polymict samples from Apollo 16 because a significant fraction (10–25%) of the Fe in Apollo 16 soils is not contained in mafic silicates but in nonuniformly distributed metal grains of meteoritic origin (Korotev, 1987b, 1994). Thus, the total concentration of Fe can vary significantly among samples of identical lithophile-element composition (Korotev and Morris, 1993; Korotev, 1994).

As discussed in more detail below, the principle sources of incompatible elements like K, Th, and the rare earth elements (REEs) in the Apollo 16 regolith are mafic impact-melt breccias, or MIMBs. Because ratios of any two incompatible elements are nearly constant among MIMB samples, concentrations of all incompatible elements are mutually correlated to a high degree (*e.g.*, Fig. 3), and terms like "Sm-poor" and "Th-rich" are used here to designate that a rock, soil, or component has low or high concentrations of all incompatible elements and, by inference, MIMBs. The MIMBs are also a major source of Fe, Mg, Sc, and related elements. Thus, from the lithologic perspective, the main cause of compositional variation among different soil samples is variation in the ratio of feldspathic lithologies to mafic lithologies (mostly MIMBs). This variation is the reason incompatible element concentrations correlate positively to a high degree with those of elements compatible with mafic minerals (Fig. 6); both suites of elements are carried mainly by the MIMBs.

All mature soils are at the Sm-rich end of the compositional range for Apollo 16 soils, that is, mature soils contain a higher proportion of MIMBs than immature soils or, conversely, immature soils are consistently more feldspathic than mature soils. The linear trend of data in two-element plots of Apollo 16 soil compositions (Figs. 3,

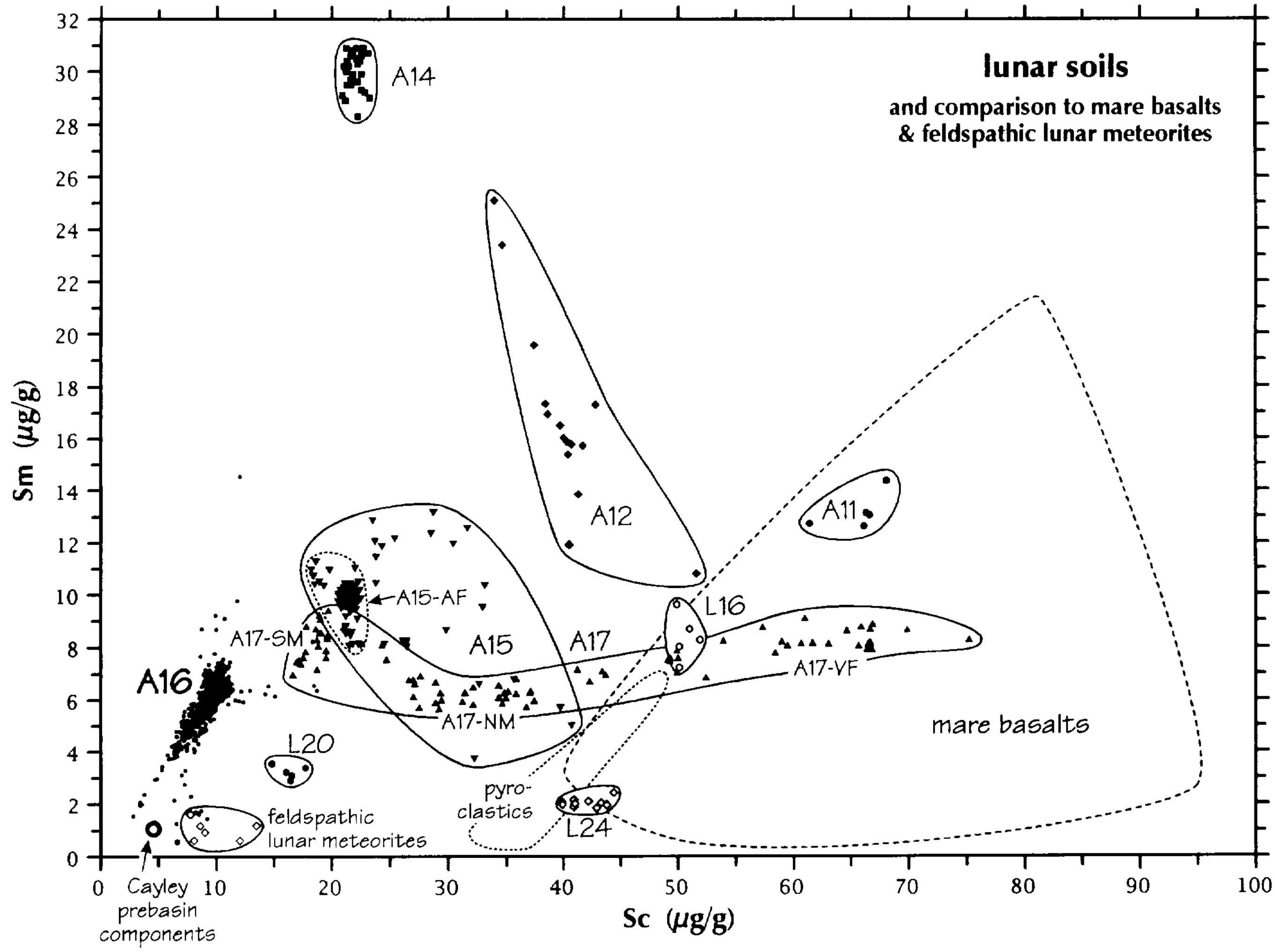

FIG. 6. The lunar regolith in Sc-Sm space. Soils (<1 mm fines) consisting predominantly of highlands materials plot at <25 μg/g Sc, for example, Apollo 16 (A16) and Luna 20 (L20), because they contain the lowest abundance of mafic minerals and minimal mare basalt; soils having >40 μg/g Sc consist largely of pulverized mare basalt. At Apollo 17, for example, soils from the South Massif (SM) contain the least mare basalt, those from the valley floor (VF) contain the most, and those from the North Massif (NM) are intermediate. The soils of Apollo 14 contain a high proportion of KREEP-bearing MIMBs (mafic impact-melt breccias), which are the principle carriers of incompatible elements like Sm in Apollo regoliths. Also shown is the range of the feldspathic lunar meteorites, all of which are regolith or fragmental breccias that contain little MIMBs and mare material compared to the Apollo and Luna soils. Apollo 16 soils are anomalous compared to typical lunar highlands (*i.e.*, the feldspathic lunar meteorites) in containing a high abundance of MIMBs (29%, Table 8), which causes them to have moderately high concentrations of incompatible elements like Sm and Th. For Apollo 16, all subsamples of surface and core soils analyzed in this lab are plotted as small dots (N = 1047). For the other Apollo sites, only surface soils are plotted, except that for Apollo 15, all samples from the station-2 core are plotted in the field labeled A15-AF (Apennine Front). Except for the core samples and soils from the Russian Luna sites, only one or two subsamples each of any five-digit sample (*e.g.*, 71501) are usually plotted. The range of known types of mare basalt is shown by the large dashed field; within this range, TiO_2 concentrations tend to increase with Sc concentration. Apollo 15 green, Apollo 16 yellow, and Apollo 17 orange glass define the field labeled "pyroclastics." All Apollo soil data are from this laboratory: Apollo 11 (Korotev, unpub.); Apollo 12 (Korotev and Rockow, 1995); Apollo 14 (Jolliff *et al.*, 1991a; Korotev, unpub.); Apollo 15 (Korotev, 1987a, 1995); Apollo 16 (references of Fig. 4); Apollo 17 (Korotev and Kremser, 1992). Data for Luna soils, mare basalts, and pyroclastic glasses were taken from Jolliff *et al.* (1993), Korotev and Haskin (1988a), Korotev *et al.* (1990a,b), and the compilation of Taylor *et al.* (1991). See Korotev *et al.* (1996) for sources of data on the feldspathic lunar meteorites.

6, and 7) reflects vertical mixing, caused by impacts, of MIMB-rich, mature surface soil of the Cayley Formation and feldspathic, immature subsurface material (Korotev, 1991a, 1996). Thus, we can conclude that the abundance of MIMBs must decrease with depth in the regolith (in the upper tens of meters, at least). A sometimes overlooked consequence of this mixing effect is that any parameter (*e.g.*, Fe-Ni metal abundance, albedo) that correlates with MIMB or plagioclase abundance is likely to show a correlation with regolith maturity and can be erroneously interpreted as implying a causal relationship to the maturation process.

LITHOLOGIC COMPONENTS OF THE APOLLO 16 REGOLITH

The Apollo 16 regolith is composed of a variety of lithologies (Heiken *et al.*, 1973; Delano *et al.*, 1973; James, 1981; Houck, 1982a; Stöffler *et al.*, 1980, 1981, 1985; Jolliff and Haskin, 1995), and many of these are compositionally distinct, although most of the nominal lithologies have a range of compositions that overlap with those of other lithologies. In this section, I summarize some features of these lithologies with respect to their importance to regolith composition.

TABLE 2. Mean concentrations of key elements in Apollo 16 regolith and some components of the regolith as used in mixing models.

	Regolith		Sm-poor feldspathic components										Sm-rich mafic components				
	MCS	ARB	FAn	NAn (noritic anorthosites)									MIMB (mafic impact-melt breccias)				
				FNAn		FFB		GrB		FIMB						
				D	C	Fe	Mg	Fe	Mg	4	3	16 2DB	16 2Mo	16 1F	16 1M	14
Note:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
TiO_2	0.595	0.51	0.01	0.18	0.06	0.37	0.38	0.32	0.25	0.36	0.34	0.93	0.72	1.20	1.37	1.0
Al_2O_3	26.7	28.4	35.5	29.8	30.4	28.0	29.6	31.3	27.3	31.1	28.7	22.0	20.5	19.3	17.1	15.9
FeO_t	5.51	4.21	0.26	4.13	4.60	5.99	2.94	3.26	3.97	2.98	4.28	8.00	6.83	8.35	9.69	10.09
MgO	6.14	5.49	0.22	3.00	4.24	3.99	4.38	2.63	7.07	2.80	4.46	10.9	14.70	9.90	13.35	11.4
CaO	15.30	16.1	19.1	17.4	16.8	17.0	16.7	17.5	14.9	17.3	16.1	12.7	11.6	12.1	10.7	10.0
Na_2O	0.457	0.49	0.38	0.34	0.24	0.36	0.56	0.51	0.47	0.53	0.49	0.49	0.45	0.54	0.62	0.815
Sc	9.64	6.61	0.37	8.6	4.7	13.0	5.0	8.34	6.77	5.4	7.9	10.8	9.69	14.8	14.6	21.3
Cr	775	524	15	500	430	696	388	475	765	360	650	1110	1170	1220	1520	1253
Co	31.7	21.8	0.47	5.8	9.8	8.2	10.2	7.9	21.1	6.9	16.9	65.8	45.4	40.8	63.9	34.4
Ni	454	296	2	9	5	10	120	32	232	43	190	1070	592	590	1090	320
Ba	146	118	8.5	17	7	27	73	47	61	42	79	265	188	514	489	971
La	13.30	11.2	0.202	0.89	0.20	1.93	4.39	2.18	3.83	2.37	6.99	27.5	18.3	54.6	49.6	87.0
Sm	6.18	5.10	0.0765	0.49	0.09	1.02	1.94	1.29	1.63	1.12	3.19	12.7	8.4	24.8	22.5	38.5
Eu	1.20	1.21	0.829	0.750	0.630	0.799	1.293	0.785	1.066	1.14	1.06	1.49	1.15	1.94	1.97	2.68
Yb	4.37	3.49	0.0333	0.50	0.12	1.00	1.59	1.06	1.64	0.91	2.35	8.56	5.93	16.8	15.4	27.9
Lu	0.608	0.49	0.0049	0.071	0.019	0.145	0.225	0.17	0.24	0.127	0.325	1.16	0.83	2.26	2.07	3.83
Th	2.22	1.76	0.010	0.10	0.02	0.22	0.70	0.18	0.91	0.37	1.16	4.3	3.1	8.8	8.1	16.7
Mg'	66.5	70	60	56	62	54	73	59	76	63	65	71	79	68	71	67

Oxides values and *Mg'* in percent, others in μg/g; FeO_t = total Fe as FeO; *Mg'* = mole percent MgO/(MgO + FeO_t). (1) Mature Cayley soil; mean of station means, from Table 1. (2) Ten samples of ancient regolith breccia (mean from Korotev, 1996). (3) Ferroan anorthosite with ~99% plagioclase (Korotev *et al.*, 1980, and 20 1–2 mm particles of this work). (4) Descartes ferroan noritic anorthosites from 67513 (Table 2, column 7 of Jolliff and Haskin, 1995). (5) Cayley ferroan noritic-anorthosite samples 60135, 62236, 62237 (Warren and Wasson, 1978; Haskin *et al.*, 1981; Warren *et al.*, 1983) and two 1–2 mm particles (this work). (6) Ferroan feldspathic fragmental breccias; calculated by regression but based mostly on samples 67455 and 67513 (Wänke *et al.*, 1973; Lindstrom and Salpas, 1981; Jolliff and Haskin, 1995). (7) Magnesian feldspathic fragmental breccias; calculated by regression but based mostly on samples 67055 and 67605 (Warren and Wasson, 1978; Lindstrom and Salpas, 1983). (8) Ferroan granulitic breccias samples 67215, 67488, 67485, 67615, and 67947 (Lindstrom and Lindstrom, 1986; Stöffler *et al.*, 1985). (9) Magnesian granulitic breccias samples 67415, 67566, 67746, 67955 (Lindstrom and Lindstrom, 1986; Stöffler *et al.*, 1985). (10–15) Apollo 16 impact-melt breccia groups (means from Korotev, 1994); group 2Mo (olivine-rich) is represented by sample 62295. (16) Apollo 14 mafic impact-melt breccia (Jolliff *et al.*, 1991a; major elements from Wänke *et al.*, 1972).

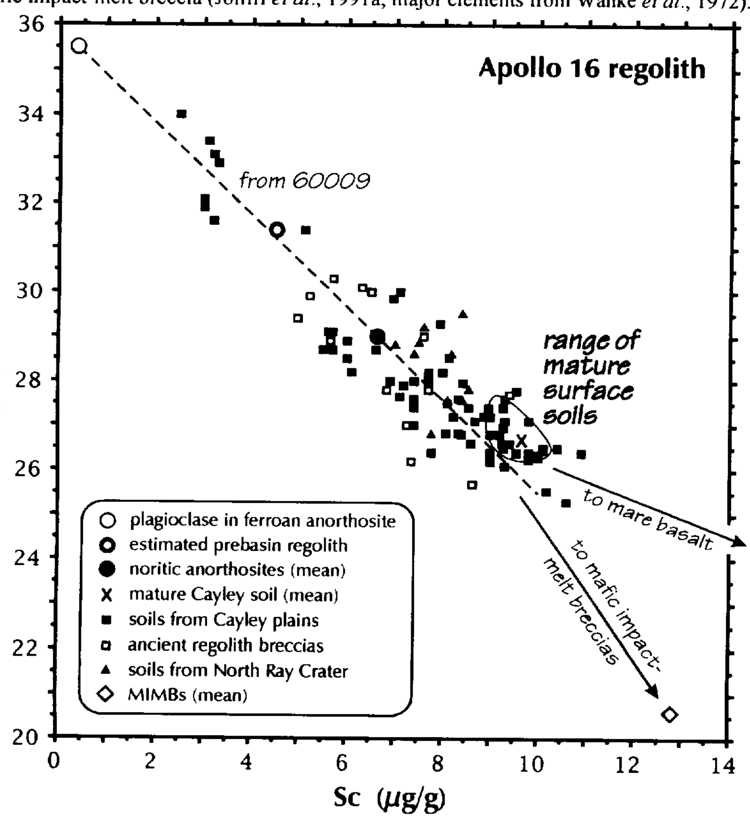

FIG. 7. Variation of Al_2O_3 and Sc concentrations in Apollo 16 regolith samples (surface soils, core soils, and regolith breccias). The anticorrelation reflects a range in normative plagioclase abundance from 95% (high-Al_2O_3 soils, from core 60009) to 70% (low-Al_2O_3, mature soils), which in turn leads to more than a factor of four variation in the concentration of Sc, which is carried mainly by pyroxenes. The diagonal line is a mixing line defined by ferroan anorthosite (open circle; Table 2) and the average composition of the noritic-anorthosite components of mature Cayley soil (filled circle; Table 7). Extrapolation of the line to 0% Al_2O_3 gives 35 μg/g Sc, which is the average concentration for the nonplagioclase phases of the nonmare components of the soil (primarily, low-Ca pyroxenes and olivine). Scandium is carried subequally by three classes of material in Apollo 16 regolith: (1) the feldspathic, prebasin components (partially filled circle at 4 μg/g Sc; Table 10, column 3), (2) mafic impact-melt breccias (MIMBs, diagonal square; Table 7, column 1), and (3) mare basalt and glass (off scale at 50–90 μg/g Sc; Fig. 6). Mature Cayley soils (mean: point X; Table 1) contain a small excess of Sc compared to the mixing line because a significant fraction of the Sc (31%) is contributed by the mare-derived components; the fraction carried by the MIMBs is similar (38%; Table 8). The small compositional range of the mature soils indicates that the ratio of mare-derived material to MIMBs is nearly constant in mature soils. Data for Sc in lunar soils are much more abundant than are data for Al_2O_3. Scandium is determined with a precision of 1–2% by INAA, but much of the available Al data, particularly for core soils, are of poorer precision (~5%). Sources of data: Ali and Ehmann (1976, 1977), Korotev (1982), McKay *et al.* (1986), Simon *et al.* (1988), and numerous sources cited in Korotev (1981).

Average concentrations of key elements in some of these lithologies are listed in Table 2. In the next section, these average compositions are used as components in mass-balance models.

Crystalline Impact-Melt Breccias

Impact-melt breccias are produced by melting of lunar material during hypervelocity impacts of meteoroids. Impact-melt breccias are the predominant lithology returned as rocks from the Apollo 16 site and are one of the most abundant components of the Cayley regolith (Ryder, 1981; Korotev, 1994). Apollo 16 melt breccias cover a wide range of compositions. Among crystalline melt breccias (*i.e.*, those most likely to have formed in the largest impacts), several compositional clusters or groupings are recognized. The following summary is based on the discussion in Korotev (1994); see Taylor *et al.* (1991) for a general discussion of impact-melt breccias.

Mafic Impact-Melt Breccias–At one extreme are the impact-melt breccias of compositional groups 1 and 2 (Fig. 5b). Such samples have historically been called basaltic impact melts, "LKFM (low-K Fra Mauro) basalts" (group 1), or "VHA (very high alumina) basalts" (group 2). The use of the word "basalt" reflects that such breccias are dominated by calcic plagioclase and pyroxene but misleadingly implies that they are extrusive volcanic rocks. The more accurately descriptive term "impact-melt breccia" is preferred (Stöffler *et al.*, 1980). Thus, I refer to breccias of compositional groups 1 and 2 as "mafic impact-melt breccias," or MIMBs, because they are at the mafic end of the compositional range of highlands melt breccias. The compositional distinction between groups 1 and 2 has been long recognized (Floran *et al.*, 1976), but recent work advocates two subgroups of group 1 (1M and 1F) and at least three subgroups of group 2 (2DB, 2NR, and 2Mo; Korotev, 1994). Thus, for the rest of this paper, I assume that there are at least five compositionally distinct groups of Apollo 16 MIMBs.

In addition to being the most mafic of the common lithologies in the Apollo 16 regolith, MIMBs are also the most Th- and Sm-rich. Although igneous KREEP basalt is not known to occur at the Apollo 16 site, MIMBs are the carrier at the site of the chemical signature associated with KREEP, which implies that KREEP basalt or ur-KREEP (Warren and Wasson, 1979b) occurred in the target area(s) of the impact(s) that formed the Apollo 16 MIMBs (Spudis, 1984; McKinley *et al.*, 1984). Apollo 16 MIMBs are generally similar in bulk composition to MIMBs from other sites but are unusual in that all the groups have considerably higher concentrations of siderophile elements because they contain a large dose, 1–2%, of Fe-Ni metal presumably derived from the impactor or impactors that formed them (Korotev, 1987c, 1994). As a result, mean Ni concentrations in groups 2DB and 1M are 3–8× greater than those for MIMBs from Apollos 14, 15, and 17. Mafic impact-melt breccias of compositional groups 1M and 1F are common components of the Cayley plains, and some were found near North Ray Crater at station 13 but not at station 11. Group 2DB is common on the Cayley plains and absent from North Ray Crater; whereas, group 2NR is the most common composition of MIMB in the North Ray Crater ejecta but is uncommon on the Cayley plains. All MIMB samples from Apollo 16 that have been dated give crystallization ages of ~3.9 Ga, that is, they were all produced at the time of basin formation and, as is discussed in more detail in a later section, some or all may be impact melt formed in major basins.

Feldspathic Impact-Melt Breccias–Melt breccias of compositional groups 3 and 4 have compositions of noritic anorthosites. They are more feldspathic than mature Cayley soil and have lower Sm concentrations, Sm/Sc ratios, and *Mg′* (FIMBs of Table 2). Both groups of feldspathic melt breccias overlap in composition with the granulitic breccias and feldspathic fragmental breccias discussed below. Feldspathic melt breccias are considerably less abundant at the site than are mafic melt breccias. Of the six known samples of group-3, four are from central and southern stations and the other two are from station 13. Most known samples of group-4 are from North Ray Crater, but this may be because the North Ray Crater samples have been studied in more detail. The feldspathic impact-melt breccias probably formed by impacts into feldspathic upper crust relatively uncontaminated by KREEP basalt or KREEP-bearing MIMBs. Some may have been produced by impacts making craters only a few kilometers in diameter (Deutsch and Stöffler, 1987).

Ferroan Anorthosite and Noritic Anorthosite

Perhaps the most characteristic rocks of the Apollo 16 regolith are the anorthosites. Anorthosite, by definition, consists of >90% plagioclase by volume (Stöffler *et al.*, 1980) and most Apollo 16 anorthosite rocks contain 95–99% plagioclase (Warren, 1990; Haskin *et al.*, 1981). Many are cataclastic in texture but not obviously polymict. Normatively, samples with >31% Al_2O_3 or <4–5 μg/g Sc are anorthosites (Fig. 7). Rocks with such a high feldspar content are not common at any other Apollo site. Anorthosite fragments are a common component of the Cayley regolith (*e.g.*, ~18% of the 1–2 mm particles of Fig. 5), and a large fraction of these particles consists entirely of plagioclase (Heiken *et al.*, 1973; Houck, 1982a). Apollo 16 anorthosites are typically called "ferroan anorthosites" because of their low *Mg′* (50–70; see Warren, 1990). Mafic variants of ferroan anorthosite (*i.e.*, ferroan noritic anorthosites consisting of <90% plagioclase) also occur at Apollo 16, but they are rarer (*e.g.*, Haskin *et al.*, 1981; Warren, 1990; Jolliff and Haskin, 1995). Ferroan anorthosite and noritic-anorthosite fragments occur both in the Cayley regolith and at North Ray Crater, and all are characterized by very low concentrations of incompatible elements such as Sm (<1 μg/g). Compositions of model components representing ferroan anorthosite (FAn) with ~99% plagioclase and two types of ferroan noritic anorthosite (FNAn) with 85–90 vol% plagioclase are included in Table 2. The FNAn-C component is based on several samples from the Cayley plains. The FNAn-D component, which is more ferroan (lower *Mg′*), more albitic, and substantially richer in Sc, is based on ferroan noritic anorthosites from North Ray Crater.

Dimict Breccias

A prevalent and important rock type of the Cayley plains at the Apollo 16 site is dimict breccia. Dimict breccias consist of two lithologies, ferroan anorthosite and group-2DB melt breccia, in a mutually intrusive relationship (Stöffler *et al.*, 1981; James *et al.*, 1984; McKinley *et al.*, 1984). Because the relative proportions of the two lithologies vary from sample to sample, no discrete component of dimict breccia is included in the models. Instead, the dimict breccias are represented by the FAn, FNAn-C, and MIMB-2DB components.

Nonmare, Mafic Plutonic Rocks

Nonmare, mafic plutonic rocks are rare at the Apollo 16 site. Among the 41 rock and clast samples from Apollo 16 that are probably endogenous igneous relicts of the ancient lunar crust ("pristine rocks"), nearly all are ferroan anorthosites or noritic anorthosites; the remainder are mafic plutonic rocks: three (spinel) troctolites and four gabbronorites (Warren, 1993; pristinity confidence index 6 or better). Most mafic plutonic rocks have been found as small clasts in fragmental breccias or as fragments in the regolith; only one, a gabbronorite, occurs as a "big" sample (7.9 g 67667; Fig. 5). Only three of the samples of pristine or probably pristine mafic rocks from Apollo 16 are from the Cayley plains; the other four are from station 11 at North Ray Crater (again, this may reflect the greater attention that has been given to station-11 samples). The gabbronorites are the most mafic nonmare rocks in the regolith; incompatible-element concentrations are highly variable (Fig. 5). Because the gabbronorite components used in the modeling (appendix) are minor components and their compositions were taken directly from the literature, the compositions are not retabulated here.

Granulitic Breccias

Granulitic breccias or granulites are a common type of nonmare rock. At Apollo 17, granulitic breccias are the main carrier of the model component called "anorthositic gabbro" (Rhodes *et al.*, 1974; Schonfeld, 1974) or "anorthositic norite" (Korotev and Kremser, 1992). At Apollo 16, granulitic breccias normatively span the range from anorthosite, through noritic and troctolitic anorthosite, to anorthositic norite (*i.e.*, 24–34% Al_2O_3) but all are characterized by low concentrations of incompatible elements (Fig. 5). Lindstrom and Lindstrom (1986) noted that granulitic breccias from Apollos 15, 16, and 17 also span a large range of *Mg′* but that there was a dichotomy between the ferroan (*Mg′* < 70) and magnesian (*Mg′* > 70) extremes. Lindstrom and Lindstrom (1986) only discuss three samples from Apollo 16, but when the data of Stöffler *et al.* (1985) are included, the Apollo 16 samples seem to verify this dichotomy: values of *Mg′* for five ferroan samples range from 56–61 (noritic anorthosites) and those for four magnesian samples range between 72–78 (troctolitic or noritic anorthosites) (Table 2). It is likely that the ferroan granulitic breccias contain a significant component of ferroan noritic anorthosite as there are many compositional similarities between the two rock types (*e.g.*, low Th/REE ratios compared to magnesian granulitic breccias). Igneous precursors for the magnesian granulitic breccias may be feldspathic rocks of the Mg-rich suite of plutonic rocks (Lindstrom and Lindstrom, 1986). Most rock-sized Apollo 16 granulitic breccias are from North Ray Crater, but they appear to be at least a minor component of the Cayley regolith based on modal petrographic studies (Houck, 1982a,b). Compositions of model components representing both ferroan and magnesian granulitic breccias (GrB-Fe and GrB-Mg) are given in Table 2.

Feldspathic Fragmental Breccias

The most common rock type excavated by the North Ray Crater impact is fragmental breccia consisting largely of plagioclase (Stöffler *et al.*, 1985). The feldspathic fragmental breccias are secondary breccias, that is, breccias containing clasts of older breccias (granulitic breccias, impact-melt breccias) as well as plutonic rocks (anorthosites, troctolites, and gabbronorites). In the feldspathic fragmental breccias of North Ray Crater, clasts of group-2NR MIMB are common; the MIMB clasts account for ~9% of the mass, on average (although the range is great), and are the main carrier of incompatible elements (Korotev, 1996). Like the granulitic breccias, feldspathic fragmental breccias have bulk compositions of noritic anorthosite and have a range of Mg/Fe ratios, probably because they contain a large component of granulitic breccia or are composed of the same precursors as the granulitic breccias. For the mixing model, two components are included (Table 2) that represent the ferroan (FFB-Fe) and magnesian (FFB-Mg) ends of the compositional range. Compositions of samples of intermediate *Mg′* (*e.g.*, 67015 and 67016) can be modeled reasonably well as mixtures of the FFB-Fe and FFB-Mg components used here, plus or minus small amounts of group-2NR impact-melt breccia. As with the granulitic breccias, rock-sized pieces of feldspathic fragmental breccias are rare among samples acquired from the Cayley plains (Ryder and Norman, 1980) and in the fine-grained regolith they are much less abundant on the Cayley plains than at North Ray Crater (Houck, 1982a). No systematic study of feldspathic fragmental breccias from the Cayley plains has been made, so it is not known whether they are compositionally similar to those of North Ray Crater and whether the MIMB clasts they contain are of compositional group 2NR, as are those from North Ray Crater.

Ancient Regolith Breccias

Some breccias from Apollo 16 are composed of regolith lithified by the heat and pressure of impacts. A few of these (*e.g.*, those of Jerde *et al.*, 1990) are similar in composition and maturity to the present soil and may have formed from it by relatively recent impacts. The study of McKay *et al.* (1986), however, showed that a number of others are "ancient" in the sense that they are composed of very old regolith. The ancient regolith breccias have high $^{40}Ar/^{36}Ar$ ratios and contain excess fission Xe, which indicate that the material of which the breccias are composed existed as fine-grained regolith ~4 Ga ago. In contrast to mature Cayley soils, the ancient regolith breccias have low values for maturity parameters such as agglutinate abundance, solar ^{36}Ar abundance, and I_s/FeO, which indicates that the surface exposure of the materials of which they are composed was of short duration. It is not known when the ancient regolith breccias were lithified. They contain MIMB clasts identical in composition to large rocks found at the site that have been dated at ~3.9 Ga (*i.e.*, compositional groups 1M, 1F, and 2DB; Korotev, 1996). Thus, lithification occurred either more recently than or contemporaneously with formation of the MIMBs. Ancient regolith breccias are similar to feldspathic fragmental breccias in that both are fragmental breccias consisting of a variety of feldspathic components and MIMB clasts. However, the types of MIMB clasts in the two types of breccia are different, MIMBs are more abundant in ancient regolith breccias (27.5%, compared to ~9% in feldspathic fragmental breccias), and the average compositions of their feldspathic components are different (Korotev, 1996). The ancient regolith breccias, which appear to be restricted to the Cayley Formation in that they are not found at station 11, are similar in composition to mature Cayley soil (Table 2), and the regolith they represent may have been a precursor to the present regolith (McKay *et al.*, 1986). However, because the ancient regolith breccias lack mare-derived material (Fig. 4), they have lower concentrations of Sc and Cr and a higher *Mg′* than the present regolith.

Mare Basalt and Glass

Although the Apollo 16 site is distant from the nearest mare basin, fragments of crystalline mare basalt of a variety of types have been found in the Apollo 16 regolith (Delano, 1975), although such fragments are rare. In the most detailed studies, Houck (1982a,b) identified no fragments of crystalline mare basalt among more than 4000 particles from Cayley surface soils (grain size: 20–500 μm, mostly 90–150 μm). Among nearly 10 000 particles from the 64002 core (0–25 cm depth), she found only 19 fragments of crystalline mare basalt (0.2%). Most of the mare-derived material that has been identified in the Apollo 16 soil is impact glass, although some pyroclastic glass also occurs (Delano, 1986). Among spherules and shards of glass that are clast free and relatively homogeneous, those of mare derivation are common; ~23% of the >20 μm glasses in 64001 (Delano, 1991a) and 16% of the 10–90 μm glasses of several Cayley soils (Kempa and Papike, 1980) are of mare composition (or mixed highlands-mare dominated by mare) based on their Ca/Al ratios.

Establishing the total proportion of mare-derived material in the Apollo 16 regolith is more difficult as estimates based on modal petrography yield different estimates than those based on composition. In part, the disagreement occurs because some mare material is contained in the glass of agglutinates and regolith breccias and, thus, is observed chemically but not petrographically. I review some other considerations here. The abundance of mare-derived material in mature Cayley soil is sufficiently high that the soil contains an excess of Sc over any combination of the constituent nonmare rocks that reasonably accounts for other elements. Even the crudest estimates suggest that there must be a few percent of mare-derived material in mature Cayley soils to account for the excess Sc (*e.g.*, Fig. 5). However, as emphasized below, the exact amount estimated is highly dependent upon assumptions about the nature and abundance of other mafic components of the soil. For example, gabbronorites are also rich in Sc, so if the abundance of gabbronorite is high, the need for mare-derived material to account for the excess Sc in the soil is reduced.

Compositional data do provide one unambiguous constraint, however. We know that the abundance of mare-derived material in surface soils of the Cayley plains is essentially constant because any significant variation would lead to variations in Sc concentrations while leaving Sm concentrations (for example) relatively unaffected. The small range of Sm/Sc ratios exhibited by mature Cayley soils (Figs. 4, 5b) indicates that the relative abundance of mare-derived material is nearly invariant from sample to sample. Only within specific regions of the 64001/2 and 60001–7 cores are there enrichments in mare material over levels seen in mature surface soils (Korotev *et al.*, 1984; Korotev, 1991a; Korotev and Morris, 1993). If the mare-derived component of the Apollo 16 regolith were part of the local pre-Imbrium regolith, then we might expect such intimate mixing by the plains-forming process. However, from arguments presented below, the absence of mare-derived material in the ancient regolith breccias suggests instead that the mare-derived material in the present regolith was added after deposition of the Cayley plains. Thus, the uniform abundance of mare-derived material probably occurs because most of it was added as fine-grained (*e.g.*, <50 μm) pyroclastic and impact glass over the last 3.9 Ga. With time, the formation of agglutinates would distribute fine-grained mare-derived glasses into larger particles, and agglutinates (below) are a major lithologic component of mature soils. Thus, the soil maturation process probably accounts for why the abundance of mare-derived material in <1 mm soils from the Cayley plains is not strongly dependent on grain size; fine grain-size fractions (<20 μm) have the same Sc concentrations as "bulk" (<1 mm) samples (Korotev, 1981).

Different petrographic studies have not led to consensus, but some studies allow for as much as ~5% mare-derived glass in mature Cayley soils. In the Cayley soils studied by Kempa and Papike (1980), 3.9% of those grains that were not "fused soil" (*i.e.*, agglutinates, regolith breccias) in the 10–90 μm grain-size fractions were glasses of mare derivation. However, the samples studied by Kempa and Papike (1980; surface soil 64501 and drive tubes 60009/10) are less mature and more feldspathic than typical Cayley soil. If the abundance of mare glass observed by Kempa and Papike (1980) is normalized to the same plagioclase abundance as that in mature Cayley soil, the mare glass proportion increases to 4.8%. In contrast, in the studies of Houck (1982a,b), ~5% of the particles that were not agglutinates in two Cayley surface soils and 7% of the particles in the 64002 samples (20–500 μm fractions) were glasses categorized as "clast and crystal free." If 20% of these are of mare origin (Kempa and Papike, 1980; Delano, 1991a), then only 1.2% of these soils is identifiably of mare origin. This inconsistency (4–5% *vs.* ~1%) must be attributed to differences in petrographic technique because, as noted above, Sc concentrations indicate that the abundance of mare material is not highly variable among samples or among grain-size fractions.

Meteoritic Material

Although meteorites are rarely observed as a preserved lithology, the Apollo 16 regolith contains several percent meteoritic material. It is important to distinguish among three sources of meteoritic material in the regolith (Anders, *et al.*, 1973): (1) the ancient basin-era component carried by MIMBs and other old crystalline breccias, (2) "macrometeorites" that have formed numerous small postbasin craters (*e.g.*, those of Fig. 2), and (3) micrometeorites responsible for regolith gardening (Morris, 1978a) and much of the maturation process. At Apollo 16, the ancient component, which occurs largely as Fe-Ni metal grains, has distinctly nonchondritic siderophile-element abundances, most notably an Ir/Au ratio about one-third of that of CI chondrites (Wasson *et al.*, 1975; Hertogen *et al.*, 1977; Korotev, 1987b,c, 1994). Most postbasin impacts (macro- and micrometeorites) have been by chondrites (Anders *et al.*, 1973; Wasson *et al.*, 1975), so the siderophile-element signatures of these components are essentially chondritic. At Apollo 16, the macrometeorite component is carried largely by glassy breccias, glass spheroids, and glassy splashes that coat some rocks. For example, among the 1–2 mm soil particles of Fig. 5 are several glass spheres from sample 66042 with up to 2000 μg/g Ni and CI-normalized Ir/Au ratios of ~1.2. They are compositionally similar to the Ni-rich "impact melt splashes" (group A) of Morris *et al.* (1986) that are believed to have formed in the South Ray Crater impact 2 Ma ago (*e.g.*, Eugster *et al.*, 1995).

In the mass-balance models presented below, the ancient meteorite component is carried implicitly by the components representing the breccias of which the soil is principally composed. The CI-chondrite component of the models represents only meteoritic material in the regolith in excess of that contributed by the ancient rocks; that is, it represents the macro- and micrometeorite contributions.

Agglutinates and Other Constructional Lithologies

Agglutinates are small (typically, <1 mm), glassy breccias formed from fine-grained regolith by micrometeorite impacts (McKay *et al.*, 1991). In mature Cayley soil, 37–60% of the particles in the 90–150 μm grain-size fraction are agglutinates (Heiken *et al.*, 1973). The regolith also contains numerous glass spheres, glassy splashes, and glassy breccias. All of these lithologies are constructional in that they appear to have formed by small impacts into the regolith or subregolith (McKay *et al.*, 1991; Morris *et al.*, 1986; Borchardt *et al.*, 1986). Thus, from the compositional viewpoint, they represent physical mixtures of the crystalline lithologies discussed above (*e.g.*, Morris *et al.*, 1986; Borchardt *et al.*, 1986), as does the regolith as a whole. Some glassy impact products in the regolith may not have formed locally (Delano, 1991a,b); they nevertheless represent crystalline lithologies from other parts of the Moon. For reasons detailed next, constructional lithologies are not included in the mixing models presented here.

QUANTITATIVE ESTIMATES OF THE RELATIVE ABUNDANCES OF REGOLITH COMPONENTS

In terms of composition, the lunar regolith can be viewed as a mixture on at least three levels (Korotev, 1987a). At one level, the regolith is a mixture of the products of primary igneous differentiation, that is, the igneous rocks of the early lunar crust, mare basalts, and volcanic glasses (plus, extralunar meteoritic material) because for most lithophile elements, the physical mixing and melting associated with meteoroid impact does not cause chemical fractionations or alter the mass balance. During the time of basin formation, some of these early primary crustal rocks were remelted and metamorphosed to form secondary rocks, that is, crystalline impact-melt breccias and other kinds of breccias. Thus at a second level, the regolith is a mixture of both igneous rocks and the products of basin formation. The second level is important because although basin-era products such as MIMBs are undoubtedly themselves mixtures of more primary lunar rocks and meteoritic material, efforts to account quantitatively for their compositions in terms of known early crustal rocks have not been successful, judging from the number of mutually inconsistent interpretations that have arisen (*e.g.*, Wänke *et al.*, 1976, 1977; Reid *et al.*, 1977; Wasson *et al.*, 1977; Ryder, 1979; Ringwood *et al.*, 1987; Korotev, 1997). Since basin formation, the lunar surface has been subjected to countless small impacts that have led to the constructional lithologies discussed in the previous section. Thus at a third level, mature regolith is a mixture dominated by tertiary lithologies such as agglutinates and other glassy breccias but with lesser amounts of secondary and primary lithologies. Using modal petrography, for example, one can directly measure the proportion of agglutinates, crystalline melt breccias, and anorthosite fragments presently in a regolith sample. However, there is no way to measure directly, for example, the ratio of anorthosite to troctolite in the protolith of the regolith. In order to "see through" impact events, compositional mass-balance arguments must be used to determine the proportions of "chemical components" representing the primary and secondary lithologies. This section describes such mass-balance models for the regolith of the Cayley plains.

Previous Models and the Problems of Modeling the Apollo 16 Regolith

It would be useful to know in some detail the relative abundances of the primary and secondary chemical components of the Apollo 16 regolith. There are various questions pertaining to lithologic abundances that relate to processes of crustal formation and redistribution of material by impact. For example, what fraction of the Cayley regolith is local pre-Imbrium material? What are the main feldspathic components of the Cayley soil? Are they the same as those in the Descartes material? What is the relative abundance of highly feldspathic (>90%) anorthosite compared to more mafic varieties? How much mare material occurs at Apollo 16? How is the element Fe distributed among these various lithologies?

In principle, these questions can be addressed using the constraints imposed by mass balance for the chemical elements, which is a technique that has been useful at other landing sites (*e.g.*, Korotev, 1987a; Korotev and Kremser, 1992). If one has independent knowledge that a soil is a mixture of exactly N lithologic components and the compositions of those components are well known, then the relative proportions of those components that best account for the composition of the soil can be obtained in a straightforward manner by simultaneously solving a set of mass-balance equations, one equation for each element. Mathematically, systems involving lunar soils are overconstrained because the number of elements exceeds the number of components (N), so the solutions (the mass fraction of each component) must be obtained by least squares techniques (Boynton *et al.*, 1975; Korotev *et al.*, 1995). In practice, such calculations are fraught with uncertainty and ambiguity at Apollo 16. One problem, emphasized in the previous section, is that many different lithologies occur in the soil and there is insufficient independent information about which of them are volumetrically important and which are not. Thus, what might have been a simple mathematical exercise becomes a "model" in that the identity of the most significant components must be assumed. The mathematical calculations simply provide the proportions of those assumed components that yield the best fit to the composition of the soil; they do not provide proof that the assumed components are actually present or occur in the calculated proportions.

There are additional problems with applying the mass-balance technique to the Apollo 16 soils regolith that can be illustrated best by reviewing previous mass-balance models. At a minimum, all models require components representing three "element associations" (Taylor and Bence, 1975): (1) a feldspathic component to provide the Al and Ca, (2) a mafic component to provide the Fe, Mg, Sc, Cr, *etc.*, and (3) a KREEP (Warren and Wasson, 1979b) component to account for the incompatible elements like K, REE, P, and Th. A volumetrically minor meteoritic component is also required to account for the siderophile elements and for fine tuning of the mass balance for some predominantly lithophile elements (Fe, Mg, Cr). Although none of the models discussed below uses the same set of components as any of the others, presumably all have been regarded by their proponents as successful in accounting for the composition of the Apollo 16 soil. Criteria for establishing model success (goodness of fit) have not been standardized, however.

Models Using Plutonic Components–Some models have used components representing igneous or plutonic ("pristine") lithologies of the ancient lunar crust. As noted above, this approach is reasonable because although the impact process destroys and alters lithologies, the compositional mass balance is not strongly affected by impact, although volatile elements may be lost and siderophile elements added. The models of Boynton *et al.* (1975), Korotev (1981), Spudis and Hawke (1981), and Stöffler *et al.* (1985) take this approach (Tables 3 and 4). All four models are similar in that they use a highly feldspathic anorthosite component and a high-Sm KREEP component such as that found at Apollos 14 or 15 (most Apollo 14 samples identified as "KREEP" are actually impact-melt breccias, not igneous rocks, however). The models differ significantly in the assumed nature of the mafic components. Boynton *et al.* (1975) and Spudis and Hawke (1981) used mafic rocks of the Mg-rich suite of lunar plutonic rocks (dunite, norite, troctolite; *e.g.*, Warren and Wasson, 1979a), all represented by Apollo 17 samples. Because each of these mafic components has a high Mg/Fe ratio (Mg' = 81–87) as well as a high Mg concentration, the two models require another mafic component with low Mg/Fe to account for the intermediate Mg/Fe ratio of the soil (Mg' = 66.5). Boynton *et al.* (1975) and Spudis and Hawke (1981) each chose to accommodate this mass-balance problem with mare basalt (Mg' = 40–50). The approach is extreme, however, in that no other sources of Fe and Mg are considered and, as a consequence, the models predict unrealistically high proportions of either the high-Mg' components (58%; Spudis and Hawke, 1981) or mare basalt (11%; Boynton *et al.*, 1975). (The model of Spudis and Hawke, 1981 is the only one discussed here that was applied not to sample data but to the composition of the Cayley plains as determined by gamma-ray spectrometry from orbit.) At the other extreme is the model of Korotev *et al.* (1980) that used a single, but hypothetical, mafic component of intermediate Mg', which is similar to a model of Wasson *et al.* (1977) for polymict breccias.

TABLE 3. Components that have been used to model the Apollo 16 regolith, with approximate compositions.

Lithology	Al_2O_3	*Mg′*	Sc	Sm	Typical samples	References
Plutonic rocks						
Ferroan anorthosite suite						
anorthosite	33–35.5	40–70	<2	<0.2	60015, 62255	B,C,D,E,F,G, H,I,J,K,L,M,N
noritic anorthosite	30	56–62	5–9	0.1–0.5	60135, 67513	E,N
anorthosite noritic (plutonic?)	24	60	17	<1	67215	J,M
Mg gabbronorite suite						
gabbronorite	13.2	70	21	0.9	61224	K,N
feldspathic lherzolite	7.6	73	24	2	67667	K,N
sodic ferrogabbro	11.5	32	32	11	67915, 67016	J,K,N
Mg-rich suite						
dunite	1.2	87	4.3–4.5	0.07	72415	F,K
norite	21	81	10	1.5	78235	I
troctolite	21	87	2.4	6	76535	I
spinel troctolite	20.6	91	2	0.6	67435	K,N
KREEP basalt	15–17	58	21	34	15386	A,I
"granite"	12	37	25	15	12013	C,E
Breccias						
Granulitic, feldspathic						
magnesian	24–32	75–78	6–8	1–2	67746, 67955	J,L,N
ferroan	27–34	56–61	7–14	1–2	67215, 67485	N
Fragmental, feldspathic						
magnesian	29	73	5–8	1–3	67055, 67605	N
ferroan	28	55	10–13	0.6	67455, 67513	N
Regolith, ancient	28	70–71	6.5	2.3	60016, 66035	N
Impact melt, mafic (MIMB)						
group 1 ("LKFM")	17–20	68–71	13–16	20–30	60315, 65015	D,E,G,L,M,N
group 1/2, generic ("LKFM")	18	70	–	13	?	B
group 2DB ("VHA")	21–23	69–71	10–12	12–14	61015, 66095	L,M,N
group 2NR ("VHA")	21–24	74–76	10–14	10–14	67556, 67775	J,L
group 2Mo ("VHA")	20	81	10	8	62295	G,L,N
group 2M ("VHA")	21	79	9	9	60335, 67556	D,L,M
Apollo 14 ("KREEP")	16–19	59–67	20–23	38–49	Apollo 14	B,C,E,F,K,N
Impact melt, feldspathic (FIMB)						
group 3	27–31	65–66	5–9	3–4	68415, 67559	L,N
group 4	30–31	61–63	4–6	1–2	67715, 67475	L
generic nor. anorth./anorth. gabbro	28	71	–	1–2	–	A,B,E
Mare basalt						
Low-Ti	9	43	40	3–4	Apollos 12 and 15	C,E,F,G,N
High-Ti	10	40	80–90	12–15	Apollo 11	F,M,N
Meteoritic	2	54	8	0.2	CI chondrite	C,E,F,H,I, K,M,N
Other soils	26,29	65–66	7,10	7,3	65501, 67xx1	H

(A) Bansal *et al.* (1972); (B) Taylor *et al.* (1973); (C) Duncan *et al.* (1973); (D) Haskin *et al.* (1973); (E) Schonfeld (1974); (F) Boynton *et al.* (1975); (G) Kempa *et al.* (1980); (H) Korotev (1981); (I) Spudis and Hawke (1981); (J) Lindstrom and Salpas (1983); (K) Stöffler *et al.* (1985); (L) Borchardt *et al.*, (1986); (M) Morris *et al.* (1986); (N) this work.

Of the four models based on plutonic rocks, only that of Stöffler *et al.* (1985) uses mafic components representing actual lithologies found at the Apollo 16 site. The model was developed primarily to explain polymict rocks and soils of North Ray Crater, but it was also applied to soils of the Cayley plains. Three different mafic components were used, all gabbronorites (Table 3). It is noteworthy that in the models of Boynton *et al.* (1975), Spudis and Hawke (1981), and Stöffler *et al.* (1985), it is implicitly assumed that virtually none of the Fe and Mg in the regolith derives from the ferroan-anorthositic suite (Warren, 1990) of lunar plutonic rocks, which is an assumption we believe to be unreasonable (Korotev and Haskin, 1988b). Also, except for the anorthosite, all of the components of the four models discussed above are either rare (gabbronorites, mare basalt, KREEP basalt) or unobserved (dunite, norite) as discrete lithologies in the regolith of the Cayley plains.

Models Using Polymict Components–In contrast to models based entirely on igneous rocks (modeling level 1) are models based largely on lithologies, mostly polymict, that occur as common constituents of the Apollo 16 regolith (modeling level 2). In all models that have used polymict components, MIMBs of compositional groups 1 and 2 have been the carriers of the incompatible elements and the KREEP signature because they are common and are the only Apollo 16 lithologies with concentrations of incompatible elements greater than those of the soil. Apollo 16 MIMBs have lower concentrations of incompatible elements than the Apollo-14 KREEP component of the models discussed above, thus a greater proportion of Apollo-16 MIMB component (mean: 36%; Table 4) than KREEP component (10–12%) is needed to supply the observed levels of incompatible elements. One consequence is that in the level-2 models, the carrier of the incompatible elements (the MIMBs) is also an important car-

TABLE 4. Summary of average results of quantitative mass-balance (mixing) models for mature Cayley soil.

	anorthositic, Sm-poor			mafic plutonic	granite	mafic, Sm-rich, impact-melt breccias (MIMBs) or KREEP			mare basalt	meteorite	Σ
	anorth.	noritic anorth.	anorth. norite			group 1 LKFM	group 2 VHA	Apollo 14 or 15 KREEP			
Boynton	67	—	—	7	—	—	—	12	11	3.7	100
Stöffler	63	—	—	22	—	—	—	12	—	3.4	100
Korotev	50	—	—	38	—	—	—	10	—	3.2	101
Spudis and Hawke	23	—	—	58	—	—	—	11	8	—	100
Duncan	—	73	—	—	0.8	—	—	12	11	3.1	100
Schonfeld (II)	—	86	—	—	<0.3	—	—	12	1–2	?	?
Taylor	50	—	7	—	—	—	42	—	—	—	100
Borchardt (6)	16	22	0	—	—	—	62	—	—	—	100
Schonfeld (I)	—	70	—	—	<0.3	18	—	—	1–2	?	?
Borchardt (7)	0	46	34	—	—	20	—	—	—	—	100
Kempa	56	—	—	—	—	21	14	—	10	—	101
Morris	36	—	23	—	—	6	31	—	1	3.4	101
this work	30	31	—	2.6	—	6	19	3.5	6	1.0	100

— = Component not used in model. *Sources*: Borchardt = Borchardt *et al.* (1986; Tables 6 and 7); Boynton = Boynton *et al.* (1975); Duncan = Duncan *et al.* (1973); Kempa = Kempa *et al.* (1980); Korotev = Korotev (1981); Morris = Morris *et al.* (1986); Schonfeld = Schonfeld (1974); Spudis and Hawke = Spudis and Hawke (1981), Andel region; Stöffler = Stöffler *et al.* (1985); Taylor = Taylor *et al.* (1973); this work = Model 1 (Table 6). Note that although Morris *et al.* (1986) used mainly polymict components, the compositions were calculated on a "meteorite free" basis, which is why the proportion of meteorite component in their model is equivalent to that of models using plutonic components.

rier of Fe and Mg, which is in contrast to the level-1 model in which the Sm-rich component is Apollo-14-type KREEP. Because the MIMBs have greater Mg/Fe ratios ($Mg' = 68–79$; Table 2) than the soil ($Mg' = 66.5$), the other Fe- and Mg-bearing components of the soil must have lower Mg/Fe ratios, on average. Also, as discussed above, gabbronorites or mare basalts are required to explain the mass balance for Sc (Fig. 5). Another consistent feature of all previous models is the inclusion of an anorthosite component consisting nearly entirely (>95%) of plagioclase. Because Borchardt *et al.* (1986) and Morris *et al.* (1986) included, in addition, more mafic anorthositic lithologies (granulitic breccias and impact melt breccias of groups 3 and 4), the proportions of highly feldspathic anorthosite predicted by their models (0–36%; Table 4) are at the low end of the range among the various models (up to 67%).

A significant difference among models using breccias as components is the choice of number and composition of components to represent the mafic impact-melt breccias. Predictably, in the models using group-1 MIMBs (higher Sm), a smaller proportion (18–20%) of MIMB component is needed than in the model using group-2 MIMBs (42–62%; Table 4). In the models of Kempa *et al.* (1980) and Morris *et al.* (1986), components representing both group-1 and group-2 impact-melt breccias are included. This is a reasonable approach because both types of breccia occur in subequal abundance in the soil, although group-2 breccias dominate (Fig. 5b). The predicted proportions of these two types of MIMBs are very different between the two models, however, because Kempa *et al.* (1980) use an unusual, troctolitic composition (group 2Mo; $Mg' = 79$; Table 2) to represent the group-2-MIMB component whereas Morris *et al.* (1986) use more typical compositions (groups 2DB and 2M).

Additional Problems with Previous Models–It is clear from the range of values in Table 4 that quantitative results of mass-balance models are highly dependent upon input assumptions and that there is no concurrence about the assumptions. Also, the Apollo 16 system is not as well constrained mathematically as, say, the Apollo 17 system because (1) there are many possible lithologies, some of which vary in composition, (2) many of the lithologies are composed of the same subcomponents (plagioclase, orthopyroxene, "KREEP") but in different proportions, (3) some lithologies are compositionally very similar to others, and (4) some lithologies (*e.g.*, group-2 MIMBs) correspond compositionally to mixtures of others (group-1 MIMBs plus some type of anorthositic component). The net result is that many different combinations of small numbers (*e.g.*, 6–10) of components can provide reasonable (but not necessarily excellent) matches to the composition of the soil, although some may be unrealistic. For example, all samples of mature soil from the central stations are nearly identical in composition and, thus, it is unlikely that the ratio of group-1 to group-2 MIMBs is highly variable among different batches of soil. Yet, results of previous mass-balance models suggest that this ratio varies considerably from sample to sample (*e.g.*, Morris *et al.*, 1986) and even among different subsamples of the same sample (Kempa *et al.*, 1980). Similarly, model-predicted abundances for anorthositic components can be highly variable among samples of nearly identical composition (*e.g.*, Borchardt *et al.*, 1986). These variations reflect high model uncertainty not actual variation in the proportion of components.

A Rational Model: Model 1

To avoid the pitfalls of previous models, I have chosen an approach that in several details is different from any used previously to model lunar soils. Because the compositional range of mature surface soils is small, it should be possible to account for the average composition of the soils very well. Thus, I have insisted on excellent model agreement (goodness of fit), within 1% (relative) for most elements. Instead of assuming that the soil is a mixture of some specific set of components, I have made almost no assumptions about which components are important and which are not and have systematically tested combinations of subsets of the components representing nearly every primary and secondary lithology that has been recognized from the Apollo 16 regolith (Fig. 5). The goal was to identify those combinations that account well for the regolith composition.

The method assumes that if components representing all primary and secondary lithologies that occur in the soil are included in the model, combinations of components that provide very good matches to the regolith composition are more likely to include volumetrically important lithologies than those that provide poorer matches. The main goals were to use mass-balance constraints to both identify and determine the relative abundances of the important components of the regolith. Details of the modeling technique are described in the appendix.

The model also includes one component not discussed earlier, Apollo-14-type mafic melt breccia. In preliminary modeling, no such component was included. However, analysis of preliminary results indicated a minor but relatively consistent model failure. Best-fit solutions for major elements were typically within 0.5% (relative) of the observed concentration and those for the REE were usually within 1%, but the Th concentration was typically underestimated by 3–4%. This result suggested the need for another component, one that was rich in Th and REE but that had a greater Th/REE ratio. Ratios of Th to REE are nearly constant for the Apollo 16 MIMBs (Th/Sm: 0.34–0.37, Table 2, columns 12–15) but are greater in the common Th-rich melt breccias found at Apollo 14 (Th/Sm = 0.43, Table 2, column 16; also Korotev and Haskin, 1988b). Inclusion of the Apollo-14-MIMB component corrected the Th/REE problem as well as provided a better fit for Ni and Co, which are in lower concentrations in the Apollo 14 mafic melt breccias than in those from Apollo 16 (Table 2). Model-independent justifications for inclusion of an Apollo-14-MIMB component are that one of the 1–2 mm particles of Fig. 5 appears to have Apollo 14 affinity (Table 5), and a similar sample occurs among a suite of recently studied 2–4-mm particles from the Cayley plains (Korotev *et al.*, 1997a). The apparent requirement for an Apollo-14-type Th-rich lithology could be satisfied as well by a component of regolith breccia because at Apollo 14 the regolith breccias and impact-melt breccias are of similar composition (*e.g.*, Jolliff *et al.*, 1991a).

First-order Results–The main conclusion to be made from the modeling exercise (Table 6) is that the average composition of mature Cayley soil can be explained best as an approximately 2:1 mixture of feldspathic lithologies and mafic impact-melt breccias (*i.e.*, 62 ± 3% feldspathic components and 29 ± 2% MIMB components). The feldspathic components consist of subequal proportions of noritic anorthosites (31 ± 9%) and highly feldspathic ferroan anorthosite (30 ± 7%; Fig. 8). In order to account for the Th/REE ratio of the soil, ~12% of the total MIMB component is the Apollo-14 type (*i.e.*, 3.5% of total). If this estimate is reasonable, the paucity of materials of this composition among the large samples indicates that the Apollo 14 component is relatively fine grained.

The excess Sc in the soil (Fig. 5; also Cr and Ti) is best explained by 5–6% of low-Ti, mare-derived components. Of the ten mare-basalt components tested (appendix), which spanned most of the range of known compositions, Apollo 15 green glass and Luna 16 aluminous mare basalt provided the best model fits (Table 6). This result should not be taken to imply that Apollo 15-type green glass, specifically, is the major type of mare-derived material in the Apollo 16 regolith. It does imply, however, that the mare-derived component of the soil is dominated by low-Ti basalts and glasses, although glasses of high-Ti composition are known to occur, particularly in the cores (Naney *et al.*, 1976; Kempa and Papike, 1980; Delano, 1991a). By linearly combining the ten mare-derived components in average proportions indicated in Table 6, the average composition of the mare-derived components can be estimated (Table 7).

TABLE 5. Instrumental neutron activation analysis results for mafic impact-melt breccias from the 1–2 mm grain-size fraction of soils from the Cayley plains.

	all group 2 1	all group 1 2	66042 ,16,15 3	65502 ,14T 4
Na_2O	0.51	0.55	0.87	0.44
CaO	13.0	12.9	10.3	10.9
Sc	10.9	13.0	26.1	21.1
Cr	1074	1040	1430	960
FeO	7.37	7.60	12.2	9.81
Co	49.9	39.6	26.8	18.8
Ni	780.0	600.0	230.0	70.0
Sr	175.0	182.0	170.0	159.0
Zr	360.0	650.0	1650.0	n.a.
Ba	252.0	422.0	920.0	1430.0
La	26.0	45.7	112.0	120.0
Ce	68.0	119.0	289.0	313.0
Sm	12.0	21.0	50.0	54.0
Eu	1.47	1.74	2.83	3.33
Tb	2.37	4.12	9.89	10.3
Yb	8.1	13.8	33.7	39.4
Lu	1.11	1.85	4.45	5.50
Hf	8.9	15.5	38.3	45.6
Ta	1.0	1.7	4.1	6.0
Ir	19.1	13.9	10.7	4.4
Au	16.6	13.0	6.9	1.6
Th	4.2	7.4	17.1	24.0
U	1.12	1.93	4.34	5.1
mass	575	101	10.1	3.5
N	60	11	1	1
Th/Sm	0.35	0.35	0.34	0.44

Values in μg/g, except oxides in percent, Ir and Au in ng/g, and mass in mg. *N* = number of particles averaged. Columns 1 and 2 contain mass-weighted means of all particles with 8–16 μg/g Sm (group-2) and 16–32 μg/g Sm (group-1); compare with Table 2. Columns 3 and 4 contain data for individual particles with concentrations of incompatible elements higher than those observed in crystalline melt breccias from Apollo 16. The 65502 particle is a homogeneous impact glass with adhering soil that has high Th/Sm and Yb/Sm ratios, like melt breccias from Apollo 14 (Table 2); about one-half the Na has been lost by volatilization.

Unlike the soils from the North Massif of Apollo 17 (Korotev and Kremser, 1992; Jolliff *et al.*, 1996), nonmare mafic plutonic rocks are not required in excess of ~3% as discrete components to account for the composition of the soil. Overall, the average composition of the nonmare mafic components is not highly magnesian (Mg' = 63.5, Table 7).

Finally, model results can be used to calculate how the chemical elements are distributed among the major classes of components (Table 8). For elements associated with mafic phases (Ti, Fe, Mg, Sc, and Cr), the MIMBs contribute about one-half of the mass and the feldspathic and mafic igneous components each supply about one-fourth. About three-fourths of the Al and Ca are provided by the feldspathic components, with the rest derived mostly from the MIMBs. As expected, ~80–90% of the incompatible trace elements are supplied by the MIMBs. Sodium and Eu are intermediate to the highly plagiophile (Al, Ca) and incompatible elements in behavior, with subequal contributions from the feldspathic and MIMB components.

The abundance of CI-chondrite component required for mass balance (~1%; Table 6) is considerably smaller than for models based on plutonic rocks (3–4%; Table 4) because, as noted earlier, the CI chondrite component, in effect, only represents meteoritic material added to the regolith since basin formation. Because Apollo 16

MIMBs are so rich in siderophile elements (Table 2), only a fraction (34%; Table 8) of the total Ni in the soil is contributed by the CI-chondrite component; most (56%) has been in the regolith in the form of MIMBs since the time of basin formation. The meteoritic component of the Apollo 16 MIMBs is not chondritic (Hertogen *et al.*, 1977; Korotev, 1987c, 1990, 1994; James, 1995, 1996); thus the "CI" component of earlier models is essentially a "total CI equivalent" based largely on Ni abundances. Based on the average of 890 μg/g Ni (Table 7, column 2), ~20% of the Fe in the Apollo 16 MIMBs is of extralunar origin (*e.g.*, Korotev, 1987c, 1990, 1994), and, thus, a total of 14–15% of the Fe in mature Cayley soil is ultimately derived from meteorites. (This estimate compares with 18% from Korotev, 1987b, using different techniques based largely on Ir and Au abundances.) Because such a large fraction of the total Fe derives from meteorites, realistic mass balance for lithophile elements cannot be achieved for Apollo 16 soils unless meteoritic components are taken into account.

TABLE 6. Model results (Model 1): Percent of model components in mature regolith of the Cayley plains.

Lithology	Component Name	Mean	±
Total mafic impact-melt breccia	*MIMB16+14*	*28.8*	*2.4*
Apollo 16 mafic impact-melt breccias	*MIMB16*	*25.3*	*2.2*
group 1F	MIMB16-1F	4.5	2.2
group 1M	MIMB16-1M	1.4	0.7
group 2DB	MIMB16-2DB	18.5	4.3
group 2Mo	MIMB16-2Mo	1.0	0.2
Apollo 14 mafic impact-melt breccia	MIMB14	3.5	0.9
Total prebasin	*NAn+FAn+NmM*	*64.5*	*2.7*
Total feldspathic	*NAn+FAn*	*61.9*	*3.0*
Total noritic anorthosite	*NAn*	*31.4*	*8.7*
ferroan noritic anorth., Cayley	FNAn-C	2.4	4.3
ferroan noritic anorth., Descartes	FNAn-D	2.1	4.6
feldspathic frag. breccia, low *Mg′*	FFB-Fe	1.6	3.4
feldspathic frag. breccia, high *Mg′*	FFB-Mg	7.6	9.4
granulitic breccia, low *Mg′*	GrB-Fe	1.1	2.5
granulitic breccia, high *Mg′*	GrB-Mg	9.7	8.2
feldspathic impact-melt breccia, group 3	FIMB-3	3.1	6.6
feldspathic impact-melt breccia, group 4	FIMB-4	3.8	6.9
Ferroan anorth. (99% plagioclase)	FAn	30.4	6.8
Total nonmare mafic plutonic	*NmM*	*2.6*	*1.5*
eucritic gabbro	EG	0.7	0.9
feldspathic lherzolite	FL	0.6	1.7
sodic ferrogabbro	SFG	1.0	0.8
alkali gabbronorite	AGN	0.1	0.2
ferroan gabbronorite	FGN	0.1	0.4
spinel troctolite	ST	0.1	0.2
Total mare-derived		*6.0*	*1.4*
Apollo 11 high-K	A11 HiK	0.0	0.2
Apollo 11 low-K	A11 LoK	0.2	0.4
Apollo 14 aluminous, group 5	A14 Al5	0.2	0.8
Apollo 15 green glass, group A	A15 GGA	3.5	1.8
Apollo 15 olivine normative	A15 ON	0.1	0.4
Apollo 15 quartz normative	A15 QN	0.0	0.2
Apollo 17 high-Ti	A17 HTi	0.0	0.1
Apollo 17 orange glass	A17 OG	0.1	0.3
Luna 16 (aluminous)	L16 Al	1.9	1.0
Luna 24 very-low Ti	L24 VLT	0.0	0.0
CI chondrite (excess)	CI	1.0	0.2
Total		100.3	0.3

Values in italics represent sums of values underneath, as indicated in the "component name" column; only values not in italics are included in the Total. "Mean" and "±" values are the means and sample standard deviations of all 682 excellent solutions (see appendix) that are taken here to represent the best overall results of the model.

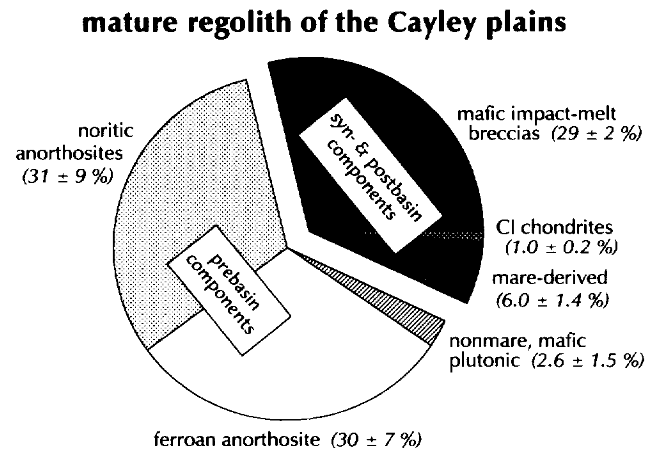

FIG. 8. Results of Model 1: Proportions of components in mature regolith of the Cayley plains at the Apollo 16 site. "Noritic anorthosites" include granulitic breccias, feldspathic fragmental breccias, feldspathic impact-melt breccias (compositional groups 3 and 4), and other rocks with 26–32% Al_2O_3. "Ferroan anorthosite" refers to ferroan anorthosite with ~99% plagioclase (~35% Al_2O_3). "Nonmare, mafic plutonic" rocks are primarily gabbronorites of the Mg-rich suite. "Mare derived" includes crystalline mare basalt, pyroclastic glass, and impact glass. "CI chondrite" represents only the meteoritic material in excess of that contributed by the breccias; it accounts primarily for the micrometeorite component of the regolith. "Mafic impact-melt breccias" includes melt breccias of compositional groups 1 and 2 ("LKFM" and "VHA") of Apollo 16 (25.3%) and a minor Apollo-14-type component (3.5%). See Table 6 for additional details.

TABLE 7. Model results (Model 1): Average compositions of supercomponents of the Cayley regolith.

	MIMB		feldspathic		mafic	
	16	16+14	NAn	NAn+ FAn	non- mare	mare
	1	2	3	4	5	6
f	25.3	28.8	31.4	61.9	2.6	6.0
TiO_2	0.99	0.99	0.29	0.15	2.6	2.4
Al_2O_3	21.2	20.6	29.0	32.2	11.3	9.9
FeO_t	8.11	8.35	3.77	2.04	12.8	19.4
MgO	11	11.1	4.85	2.57	12.5	13.1
CaO	12.5	12.2	16.25	17.7	9.3	9.8
Na_2O	0.51	0.54	0.47	0.42	0.81	0.28
Sc	11.7	12.8	6.63	3.6	26.9	49.0
Cr	1160	1170	560	290	1600	2990
Co	60	57	13.3	7.0	18.0	54
Ni	970	890	128	66	43	128
Ba	318	398	54	32	211	91
La	33.2	39.7	3.48	1.87	14.3	6.25
Sm	15.2	18.0	1.56	0.83	7.22	4.71
Eu	1.58	1.72	1.05	0.94	1.69	1.21
Yb	10.3	12.4	1.37	0.71	5.62	3.65
Lu	1.39	1.69	0.20	0.102	0.843	0.524
Th	5.26	6.65	0.64	0.33	2.12	0.50
Mg′	70.8	70.2	69.6	69.2	63.5	54.7

Oxides values and *Mg′* in percent, others in μg/g; FeO_t = total Fe as FeO; *Mg′* = mole percent MgO/(MgO + FeO_t). The compositions were calculated by linearly combining the various subcomponents of each type in the proportions of Table A2b, column 3. (1, 2) mafic impact-melt breccias (16 = Apollo 16 type, *etc.*); (3) noritic anorthosite; (4) noritic anorthosites plus ferroan anorthosite; (5) nonmare, mafic plutonic; (6) mare-derived basalts and glasses. *f* = fraction of component (from Table 6).

TABLE 8. Model results (Model 1): Percent of element carried by each class of component in mature Cayley soils.

	MIMB	feld-spathic	non-mare mafic	mare derived	CI	Σ
Plagiophile						
Al	22	75	1	2	0	100
Ca	23	71	2	4	0	100
Na	34	57	5	4	2	102
Eu	41	49	4	6	0	100
Pyroxophile						
Ti	48	16	11	24	0	100
Fe	44	23	6	21	6	100
Mg	52	26	5	13	4	100
Sc	38	23	7	31	1	100
Cr	43	23	5	23	5	100
Siderophile/lithophile						
Co	52	14	1	10	22	100
Ni	56	9	0	2	34	101
Incompatible lithophile						
Ba	78	13	4	4	0	99
La	86	9	3	3	0	100
Sm	84	8	3	5	0	100
Yb	82	10	3	5	0	100
Lu	80	10	4	5	0	99
Th	86	9	2	1	0	99

Second-order Results–Eight different components of noritic-anorthosite composition were tested in the model (Table 6). Among these, the components representing magnesian granulitic breccias and magnesian feldspathic fragmental breccias provide better mass balance than their ferroan counterparts. Model results suggest that feldspathic impact-melt breccias of groups 3 and 4 are probably only minor components of the regolith (sum: ~7%). Mass balance does not provide a strong constraint on the ratio of ferroan anorthosite to noritic-anorthosite components (0.97 ± 0.34), but the sum of these two classes of components is tightly constrained to be 62 ± 3%, thus leading to a total feldspathic component with 32% Al_2O_3 (Table 7, column 4).

For most of the nonmare mafic components, the uncertainties in the abundances are of the same magnitude as the abundances, and the abundances are all low (Table 6). The sodic ferrogabbro component is favored slightly (1% abundance). In addition to being rich in Na, the sodic ferrogabbro is relatively rich in Ba compared to other incompatible elements. Without the sodic ferrogabbro component, the model tends to underestimate the Ba concentration of the soil.

The model overestimates the concentration of Na by ~2% (relative; Table A1). Overestimation of Na concentrations occurs even when the sodic ferrogabbro is not included in the model. I take this as weak evidence that there was net loss of Na from the regolith from impact volatilization (Morgan *et al.*, 1988; Sprague, 1990), that is, that mature regolith contains slightly less Na than the mixture of rocks from which it is composed. For this reason, I weighted Na less heavily in the model than other elements primarily associated with major mineral phases.

Constructing the Present Regolith from the Ancient Regolith: Model 2

A major petrographic difference between the present regolith and the ancient regolith breccias is that the soils contain crystalline mare basalt and mare-derived glass, while the breccias contain only a trace of these lithologies (Simon *et al.*, 1988; Wentworth and McKay, 1988). Compared to the ancient regolith breccias, mature Cayley soil has significantly greater concentrations of Sc and Cr (Fig. 4), somewhat greater concentrations of Fe, Mg, and incompatible elements, a lower concentration of Al, and lower Mg/Fe and La/Sm ratios (Table 2). These observations led McKay *et al.* (1986) to conclude that the composition of present soil is most easily explained by addition of mare material to the ancient regolith. Mare-derived material accounts qualitatively for all the observed differences except the differences in incompatible elements, and these can be accommodated by a greater proportion of MIMBs in the present regolith. Ancient regolith breccias were not included as a component of Model 1 because the goal of that model was to account for the regolith as mixtures of more primary lithologic components.

In order to test quantitatively whether the present regolith of the Cayley plains could be formed by adding small amounts of other materials such as mare basalt to ancient regolith with the composition of the ancient regolith breccias, I employed a second mass-balance model. Details of the model are described in the appendix, but in essence, the noritic-anorthosite components of Model 1 were eliminated and replaced by a single component representing the ancient regolith breccias (Table 2; normatively, ancient regolith breccias are noritic anorthosites). Results of Model 2 are summarized in Table 9 and details are presented in Table A1.

Model 2 demonstrates that the composition of mature Cayley soil can be explained well as a mixture dominated by ancient regolith (71 ± 5%) but with lesser amounts of other components: Apollo-16-type MIMBs (5 ± 3%), Apollo-14-type MIMB (4 ± 1%), highly feldspathic ferroan anorthosite (12 ± 3%), low-Ti mare-derived material (7.0 ± 0.5%), and CI chondritic material (1.2%).

TABLE 9. Summary of results for mass-balance Model 2, which tests whether ancient regolith breccias might be a significant component of the Cayley regolith.

	mean	±
Ancient Regolith Breccia	71	5
MIMB16	4.8	2.5
MIMB14	4.1	0.7
FAn	12	3
Mare Derived 1	1.4	0.6
Mare Derived 2	3.0	1.8
Mare Derived 3	2.7	1.3
CI	1.2	0.1
Σ	99.9	0.1
χ^2/ν	0.80	—
$f_{2/(1+2)}$	51	35
Mare Derived	*7.0*	*0.5*
A11 HiK	0.1	0.3
A11 LoK	0.1	0.2
A14 A15	2.0	1.0
A15 GGA	3.8	1.6
A15 ON	0.2	0.5
A15 QN	0.3	0.8
A17 HTi	0.2	0.3
A17 OG	0.1	0.3
L16 Al	0.2	0.5
L24 VLT	0.0	0.0

Values in mass percent. This table summarizes means and sample standard deviations (±) for all excellent fits (*i.e.*, $\chi^2/\nu < 1$; see appendix). The value $f_{2/(1+2)}$, the fraction of group-2 MIMB in the MIMB16 component, is essentially unconstrained; any value provides some excellent fits.

Note that Model 2 is not contradictory to Model 1; it merely requires that all of the noritic anorthosite and most of the anorthosite, Apollo-16-MIMB, and nonmare igneous components of the Cayley soil came from the ancient regolith. The abundances of postbasin components (*i.e.*, mare-derived: 6% in Model 1 *vs.* 7% in Model 2; and CI chondrite material: 0.9% *vs.* 1.2%) are essentially the same in both models, as is the abundance of Apollo-14-type MIMB (3.4% *vs.* 4.1%). If any of the noritic-anorthosite components (*e.g.*, magnesian granulitic breccia) had been included as discrete additional components in the model, they would substitute for the ancient-regolith-breccia component, reducing the model-predicted abundance of ancient regolith. Thus, 71% is essentially the upper limit to the proportion of ancient regolith that can occur in the present regolith; the actual proportion may be much less.

If the present regolith derives from regolith represented by the ancient regolith breccias, the results of Model 2 provide three important constraints: (1) the mare-derived and Apollo-14-type components in the present regolith were added after closure of the ancient regolith breccias, (2) the proportion of ancient regolith in the present regolith cannot exceed ~71%, and (3) the remaining 29% is dominated by nonmare materials that occur in significantly different proportions than they do in the present regolith, which indicates some significant postclosure redistribution of highland material.

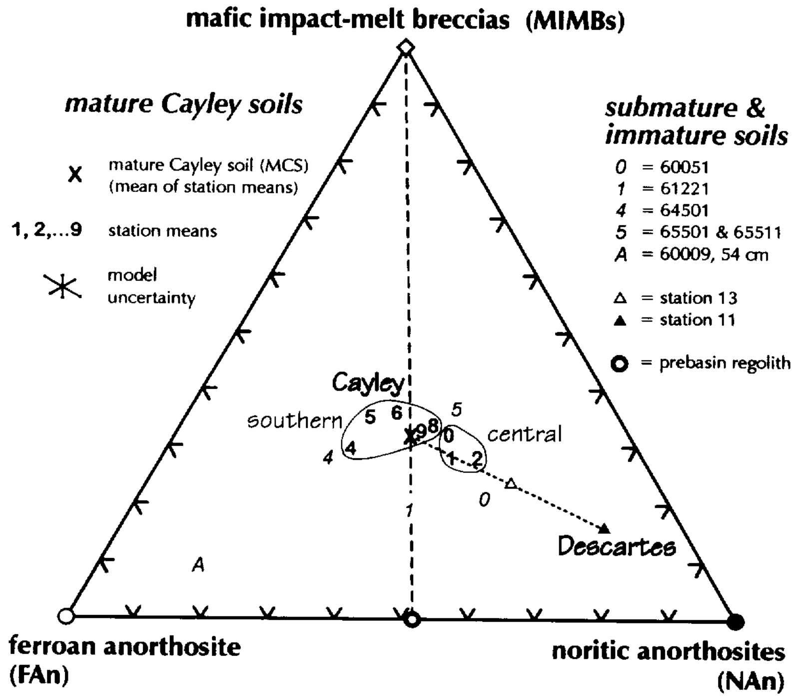

FIG. 9. Mixing model results (modified Model 1; see text) for mature soils from sampling stations on the Cayley plains and comparison to some immature and submature soils from Apollo 16 (data of Table 1). For mature Cayley soils, ~91% of the mass is carried by the three supercomponents depicted here; the other components (mafic and meteoritic) lie out of the plane (*cf.*, Fig. 7). The numbers represent the sampling stations of Fig. 2 (0 = LM station). The plot shows that mature soils from the southern stations have a greater FAn/NAn ratio than those from the central stations but that the proportion of MIMBs is relatively constant among all mature soils. Material of the Descartes Formation, as represented by the soils from station 11 at North Ray Crater (mean composition from Korotev, 1996), consists largely of disaggregated feldspathic fragmental breccia, one of the noritic-anorthosite components; thus, the station-11 soil (filled triangle) plots near the NAn apex of the triangle. The short-dashed line (see also Fig. 10) represents the Cayley-Descartes mixing line, and the soil of station 13 falls along this line because it is a mixture of Cayley regolith and North Ray Crater ejecta. All of the compositionally anomalous surface soils (*e.g.*, 60051, 61221, *etc.*) are submature or immature. The immature soil from 54 cm depth in the 60009/10 core (*A*) is the most feldspathic soil obtained at Apollo 16 (McKay *et al.*, 1976, 1977; Korotev, 1991a). The Cayley "prebasin regolith" (Table 10, column 3) is mature Cayley soil (MCS) minus the syn and postbasin components (MIMBs, mare-derived, and CI chondrite); thus, in this projection, it plots on the FAn-NAn edge along the extension of the tie line from the MIMB apex through the MCS point. The error bars represent ±1-standard-deviation model uncertainties. With I_s/FeO = 61, 64501 is "officially" a (marginally) mature soil (Morris, 1978b) but is depicted here as submature (also, on Fig. 4).

DISCUSSION

Station-to-Station Variations and Subsurface Lithologic Units

For the purpose of identifying the important chemical components of the soils, the model described above was applied to the mean composition of all mature surface soils because, to a first approximation, all such soils from the Apollo 16 site are similar in composition. To a second approximation, however, small intrastation differences occur (Table 1, Fig. 4). To demonstrate how these compositional differences relate to lithologic components, I have applied a modified version of Model 1 to the station-mean compositions of Table 1. The modified model differs from Model 1 in that the noritic anorthosite, Apollo 16 MIMB, nonmare plutonic, and mare-derived supercomponents were each represented by a single composition, based on the results of Model 1 (Table 7, columns 1, 3, 5 and 6).

The model results show that some of the compositional variation that occurs among the mature soils (*e.g.*, Fig. 4) reflects differences in the ratio of ferroan anorthosite to noritic-anorthosite components; that is, mature soils from the central stations are relatively richer in noritic-anorthosite components, whereas soils from the southern stations are richer in ferroan anorthosite (Fig. 9). Although central-area soils plot along the Cayley-Descartes mixing line of Figs. 4 and 9 (*i.e.*, the line defined by the mean composition of the Cayley soils, MCS, and North Ray Crater soils), it is unlikely that any substantial portion of the excess noritic-anorthosite component in the central-area soils is actually North Ray Crater ejecta. Mature soil with a composition similar to the soil at the surface occurs to a depth of 40 cm in the 60013/14 core (LM station), which is too deep to be influenced by North Ray Crater (Stöffler *et al.*, 1981), and a zone rich in noritic anorthosite occurs at half a meter depth in the core (Korotev and Morris, 1993). Also, immature (61121) and submature (60051) soils with an excess of noritic-anorthosite components (compared to the MCS mean) occur on the edges of craters at the central stations (Fig. 9). Thus, it is more likely that material such as that excavated by North Ray Crater also underlies the central stations and was excavated by the larger (~1 km) local craters such as Spook and Flag (Fig. 2).

To the south, mature soils from station 4 contain an excess of ferroan anorthosite component compared to average Cayley soil, and sample 64501 from station 4 is even more extreme. However, ferroan anorthosite enrichment is not restricted to the southern stations. All three cores from the LM area contain layers with anorthosite enrichments (Korotev and Morris, 1993), with the immature soil at 54 cm depth in the 60009/10 core being the most extreme (Fig. 9). These enrichments suggest that there is a source of highly feldspathic ferroan anorthosite under the central stations, as well as a source of noritic anorthosite. What is not clear, however, is whether the anorthosite derives from subsurface blocks that are part of the Cayley Formation (*i.e.*, presumably emplaced by Imbrium) or whether it derives from beneath the Cayley Formation, perhaps representing some heterogeneity in the Descartes Formation.

Uniformity of the Abundance of Mafic Impact-Melt Breccias

The most significant aspect of the model results depicted in Fig. 9 is that the ratio of MIMB to anorthositic components (FAn + NAn) in mature soils is not highly variable across the site. In Model 1, the fraction of MIMB component is 29% for the average mature soil (Table 6) and the modified model shows that this value, in fact, represents a narrow range, from 25% at stations 1 and 2 to 32% at stations 5 and 6. By comparison, at the Apollo 17 site where units of mafic melt breccia appear to be concentrated at the tops of the massifs (Rhodes *et al.*, 1974; Jolliff *et al.*, 1996), the abundance of the MIMB component is more variable among soil samples. For example, among nonmare components of the massif soils, the South Massif soils contain 42–52% MIMB component (range among light-mantle stations 2, 2a, and 3), whereas the soils of the North Massif across the valley contain 27–31% (stations 6, 7, and 8; Korotev and Kremser, 1992). Thus, among the nonmare components, there is nearly a factor-of-two range across the Apollo 17 site in the proportion of MIMB component in the regolith.

At both the Apollo 15 and 17 sites, which are at major lithologic boundaries, there are clear compositional mixing trends in the regolith that reflect the mare-highlands interface (Korotev, 1987a; Korotev and Kremser, 1992). Even at the Apollo 12 site, a mixing trend between mare basalt and some KREEP-like (high-Sm) component is clearly evident in the soils (Fig. 6). At Apollo 16, there are mixing trends involving ferroan anorthosite, noritic anorthosites, and mare-derived material; however, there is no mixing trend involving the MIMBs (Fig. 10). That is, there is no soil unit substantially enriched in MIMBs over the 25–32% characteristic of mature Cayley soils. This uniformity is strong evidence that (1) the MIMBs are not an exotic lithology added to the site by postbasin impacts, as is the KREEP component of Apollo 12 (Wentworth *et al.*, 1994), and (2) there are no extensive, shallow, subsurface deposits (blocks, sheets, lenses) of "pure" MIMB in the vicinity of the site, as there appears to be for anorthosite and noritic anorthosite; MIMBs always occur in conjunction with feldspathic lithologies. Similarly, if rocks of the Mg-rich suite (troctolites, norites, gabbronorites) are a substantial component of the regolith of the Cayley plains, then they are subcomponents of the breccias of which the soil is largely composed; that is, there is no evidence in the regolith for a concentration of "pure" Mg-suite rock, as might occur for a local, near surface pluton).

In fresh ejecta (*i.e.*, immature regolith), there is evidence for some kilometer-scale subsurface heterogeneity in the distribution of type of melt breccia. The North and South Ray impactors each intercepted a block or unit of MIMB-bearing feldspathic breccia in which the MIMB component is dominated by a single compositional group. Clasts of mafic melt breccia in the feldspathic fragmental breccias of North Ray Crater are nearly entirely of group 2NR (Korotev, 1994), whereas a principal lithology in the ejecta of South Ray Crater (~10 km away, Fig. 2) appears to be dimict breccia containing mafic melt breccia of group 2DB (James, 1981; Eugster *et al.*, 1995). However, group 2DB is not confined exclusively to the South Ray Crater area because MIMBs of identical composition occur throughout the Cayley regolith (Fig. 5b; Korotev *et al.*, 1997a,b), even to a depth of 2 m at the LM area (Korotev, 1991a), which is too deep to be ejecta from South Ray Crater (Stöffler *et al.*, 1981). Thus, group-2DB melt breccia is not uniquely confined to South Ray Crater ejecta.

Despite these subsurface heterogeneities evident from immature (*i.e.*, less well mixed) regoliths, the compositional similarity of mature Apollo 16 soils collected several kilometers apart indicate that

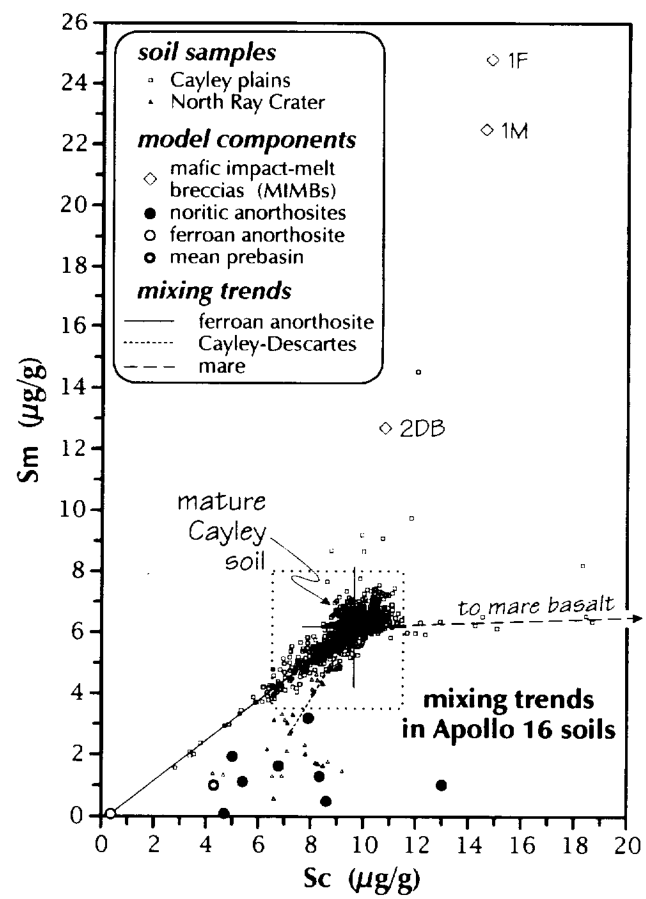

FIG. 10. Mixing trends in Apollo 16 soils. This plot includes data for all Apollo 16 soils samples (<1 mm fines) analyzed in this laboratory (mostly from cores); some of the North Ray Crater (NRC) data are from other sources (see Korotev, 1996, for sources of NRC data). The dotted box represents the range of Fig. 4. The ferroan anorthosite, the eight noritic anorthosite, and the three most abundant MIMB model components are shown, along with the estimated prebasin regolith composition (*cf.*, Fig. 9). The crossed horizontal and vertical lines indicate the average composition of mature Cayley soil (MCS). The strongest mixing trend is that between mature Cayley soil and ferroan anorthosite; this trend is defined mostly by soils from the 60009/10 and 60001–7 cores (Korotev, 1991a). There is a diffuse mixing trend between mature Cayley soils and the noritic anorthosites that is defined largely by the NRC soils (triangles) but also by soils from the central stations (Fig. 4), including core 60013/14 (Korotev and Morris, 1993). This Cayley-Descartes trend is also indicated in Figs. 4 and 9; the line terminates at the average composition of soils from station 11 (2.8 μg/g Sm). The compositional dispersion of the NRC soils reflects their immaturity (*i.e.*, the components of the NRC soils are not well mixed). A third mixing trend tends toward mare basalt; this trend is defined by stratigraphically adjacent samples from cores 64001/2 and, to a lesser extent, 60001–7 (Korotev *et al.*, 1984; Korotev, 1991a). A few soil samples plot in the direction of the MIMBs. Each is a small core sample in which stratigraphically adjacent samples (5 mm distance) are normal. Thus, this MIMB "trend" is not a mixing trend in the sense of the other trends but reflects a few random samples containing large nuggets of mafic impact-melt breccia. Although MIMBs are a major component of the Cayley regolith, there is no evidence here for a concentrated local source of mafic melt breccia, as there is for ferroan anorthosite and noritic anorthosites; the MIMB components are well mixed everywhere into the Cayley regolith.

the relative distribution of rock types in a volume of regolith of several square kilometers on the surface and extending to the depth sampled by post-Imbrium local craters (*i.e.*, tens to hundreds of meters) is similar to that of any such adjacent volume. The importance of this observation is that this high degree of homogenization, particularly, the nearly constant ratio of MIMB to feldspathic components, must be inherent to the Cayley Formation; that is, it must have been achieved at the time the plains were formed, not by any mixing of stratified feldspathic and MIMB components by post-Imbrium impacts.

Prebasin Regolith

Based on studies of feldspathic lunar meteorites (Palme *et al.*, 1991; Jolliff *et al.*, 1991b; Korotev *et al.*, 1996), we can infer that in regions of highlands distant from mare basins, the regolith is dominated by lithologies of the early upper crust and their brecciated derivatives. What can the Apollo 16 regolith tell us about the primordial crust on the Central Highlands? Addressing this question is complicated by the variety of syn- and postbasin materials in the regolith of the Cayley plains. Three of the model components represent materials added to the surface regolith during or after the time of basin formation (Fig. 8): (1) the mare-derived materials are clearly postbasin contaminants, (2) because the CI-chondrite component accounts for all siderophile elements not contributed by the rock components, it largely represents meteoritic material added to the regolith since the time of basin formation, and (3) the MIMBs were created at the time of basin formation and were probably direct products of basin-forming impacts (next section). From the point of view of understanding the typical feldspathic upper crust of the early Moon, however, the MIMBs are also "contaminants" because they represent either material from deep within the crust (*e.g.*, Spudis and Davis, 1986) or from an anomalous region of the crust (Korotev, 1997; Haskin, 1997a,b). Only the feldspathic and the nonmare mafic components represent the early upper crust. The model results allow us to calculate (Table 10) the average composition of the prebasin components of the Cayley regolith by "removing" the syn and postbasin components.

The estimated composition of the prebasin regolith obtained here from mature Cayley soil (Table 10, column 1) is very similar to one obtained from a different dataset, the ancient regolith breccias (column 2; Korotev, 1996). Both estimates suggest that, on average, the prebasin components of the Cayley plains are highly aluminous (31.4% Al_2O_3; Fig. 7), have low concentrations of incompatible trace elements (Fig. 10), and have a Mg/Fe ratio (Mg' = 68–69) at the high end of the range for ferroan-anorthositic-suite rocks. Both estimates also closely resemble estimates for "primordial upper crust" obtained in a similar manner but based on samples from North Ray Crater (columns 4 and 5; Stöffler *et al.*, 1985).

The estimated average composition of the prebasin components of the Cayley plains is generally similar to compositions of the most feldspathic of the lunar meteorites (Table 10), which indicates that the present Apollo 16 regolith differs from that of the source areas of the meteorites primarily in containing a high fraction of mafic melt breccias and mare-derived materials. The principal difference between the Cayley prebasin components and the feldspathic lunar meteorites is that the Cayley prebasin components are more feldspathic (31.4% Al_2O_3, *vs.* 28–29%) because of the high abundance of highly feldspathic ferroan anorthosite that is common in the Apollo 16 regolith (30%, Fig. 8). In bulk composition, the feldspathic lunar meteorites overlap with the noritic-anorthosite components of Model 1. In fact, a reasonable approximation to the composition of the present Cayley regolith can be obtained by substituting a generic component of feldspathic lunar meteorite (*e.g.*, the three compositions of Table 10) for the noritic-anorthosite components of Model 1 (Table 2). If our small set of feldspathic lunar meteorites is representative of regions of the highlands distant from basins, then both the Cayley and Descartes Formations contain an excess of ferroan anorthosite (Korotev, 1996).

Source of Apollo 16 Mafic Impact-Melt Breccias: Imbrium

As noted in the Introduction, the relative amounts of Imbrium, Nectaris, and Orientale ejecta in the Cayley plains is still not known. The uncertainty derives in part from a lack of consensus over the origin of the MIMBs which, along with their comminuted and rebrecciated remains, are a principal lithology of the regolith of the Cayley plains (Figs. 5, 8). There are four hypotheses for the provenance of the Apollo 16 MIMBs: (1) all are from Nectaris, (2) some are from Nectaris and some are from Imbrium (3) all or most are from local craters, and (4) all are from Imbrium. Any model for the origin of the Apollo 16 MIMBs must account for a bewildering set of

TABLE 10. Model results (Model 1): Estimate of the composition of the prebasin components of mature Cayley soil (column 1), and comparison to some other estimates and examples of lunar highlands surface materials relatively uncontaminated by syn and postbasin products.

	Apollo 16 prebasin regolith			Stöffler *et al.*		Lunar meteorites		
	Cayley *via* MCS 1	Cayley *via* ARB 2	Descartes *via* FFB 3	"West" 4	"East" 5	MAC 88105 6	QUE 93069 7	Yamato 86032 8
TiO_2	0.25	0.30	0.39	0.27	0.26	0.23	0.24	0.18
Al_2O_3	31.4	31.4	29.9	30.9	32.0	28.1	29.0	28.7
FeO_t	2.49	2.64	3.39	2.3	1.75	4.28	4.38	4.27
MgO	3.02	3.34	3.57	4.0	1.75	4.05	4.52	5.19
CaO	17.4	17.6	16.8	17.5	18.2	16.4	16.8	16.4
Na_2O	0.43	0.48	0.54	0.4	0.4	0.34	0.35	0.44
Sc	4.5	4.5	6.5	5.0	4.6	8.6	7.75	8.3
Cr	350	270	370	362	278	640	605	680
Co	7.7	6.8	6.4	6	3.8	15.0	22.0	14.5
Ni	56	32	37	44	17	155	295	134.
Ba	40	32	42	24	24	32	41	26
La	2.31	1.89	1.83	1.29	1.25	2.56	3.35	1.26
Sm	1.08	0.80	0.80	0.64	0.62	1.18	1.62	0.62
Eu	0.985	1.05	1.14	0.91	0.94	0.79	0.83	0.93
Yb	0.88	0.60	0.90	0.54	0.51	0.99	1.21	0.60
Lu	0.140	0.107	0.129	0.08	0.075	0.144	0.169	0.086
Th	0.43	0.26	0.29	—	—	0.39	0.52	0.21
Mg'	68.4	69.3	65.3	75.6	64.1	62.8	64.8	68.4

Oxides in mass percent, others in μg/g. FeO_t = total Fe as FeO. Mg' = mole percent $MgO/(MgO + FeO_t)$. (1) MCS composition of Table 2 with the syn and postbasin (MIMB, mare-derived, and CI chondrite) components removed in the proportions of Table 6 (Model 1). (2) Estimate of the average composition of the prebasin components of the Apollo 16 ancient regolith breccias (Korotev, 1996). (3) Estimate of the average composition of the prebasin components of the Descartes formation, as represented by the feldspathic fragmental breccias of North Ray Crater (Korotev, 1996). (4, 5) Estimates for "primordial upper crust" of Stöffler *et al.* (1985), using similar procedures, but based on North Ray Crater materials. (6–8) Compositions of the three most feldspathic lunar meteorites: (6) MAC88105 (mean based on Jolliff *et al.*, 1991b; Koeberl *et al.*, 1991; Lindstrom *et al.*, 1991; Palme *et al.*, 1991; and Warren and Kallemeyn, 1991; (7) QUE 93069 (Korotev *et al.*, 1996); (8) Yamato-86032 (mean based on data of Koeberl *et al.*, 1989, 1990; Warren and Kallemeyn, 1991; and Korotev *et al.*, 1996).

observations, many of which are discussed in detail in Korotev (1994) and others of which are reviewed here. In this section, which is admittedly more speculative than other sections of the paper, I argue (in contradiction to a conclusion of Korotev, 1994) that the Apollo 16 group-1 and group-2 impact-melt breccias derived from the Imbrium region during formation of the Cayley plains and, thus, that at least 25% of the material of the Cayley plains is Imbrium ejecta. I arrive at this conclusion by showing that the three alternative hypotheses are all less likely, at least from the geochemical perspective. The discussion assumes that the Cayley Formation is primarily a continuous ejecta deposit produced by the Imbrium impact.

Hypothesis 1: Nectaris–The hypothesis that all Apollo 16 MIMBs might derive from Nectaris (Spudis, 1992) follows from the observation that Nectaris is the closest basin to the Apollo 16 site (Fig. 11) and that ejecta from the basin have strongly influenced the site (Spudis, 1984; Spudis *et al.*, 1989). Hypothesis 1 implicitly assumes that (1) the crust is stratified, being progressively more mafic with depth, and, consequently, that an impact as large as the Nectaris impact produced melt that was more mafic than the local surface material and (2) the impact also sampled a source of KREEP (Ryder and Wood, 1977; Spudis and Davis, 1986).

The occurrence at the Apollo 16 site of different compositional groups of MIMBs is not necessarily inconsistent with their origin from a single basin (Hypotheses 1 and 4). If the Apollo 16 MIMBs are basin melts, then they must be samples of impact melt that were ejected from a basin at the time the basin formed because the proportion of MIMBs is too high and too uniform in the Apollo 16 regolith for the MIMBs to have been formed first as part of a melt sheet in a basin (Imbrium or Nectaris), then to have been ejected by post-basin impacts into that melt sheet, delivered to the Apollo 16 site and mixed with local materials. Because our notion of homogeneity of impact melt is based largely on melt pooled within, not ejected from, small terrestrial craters and there is no evidence that a basin-forming impact does or should eject homogeneous impact melt, the occurrence of different compositional groups is not compelling evidence against their formation in a single impact event (Spudis, 1992; Korotev, 1994; Rockow and Haskin, 1996). Also, if it is assumed that each of the compositional groups represents a single unit of impact melt (Korotev, 1994), then geochronologic data are not inconsistent with the single-impact hypothesis. Nearly all dated samples of Apollo 16 MIMBs have crystallization ages of ~3.9 Ga, and there is no evidence that any of the compositional groups represent an impact that is different in age from any of the rest, although reported ages for samples differ by amounts that are significant with respect to their stated uncertainties (*e.g.*, James, 1981; Reimold and Nieber-Reimold, 1984; Stöffler *et al.*, 1985).

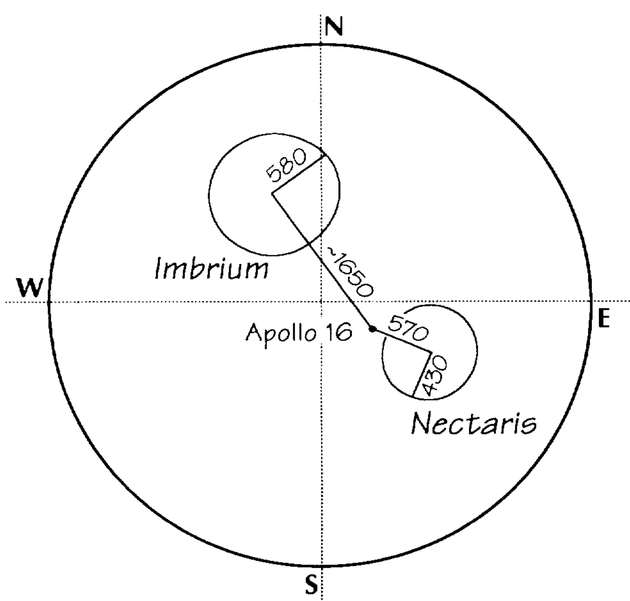

FIG. 11. Schematic map of the nearside of the Moon showing the relative locations of the Imbrium and Nectaris basins relative to the Apollo 16 site (values in kilometers). Basin radii (main topographic rims) are from Spudis (1993).

There are more serious obstacles to Hypothesis 1 than compositional groupings and crystallization ages of the MIMBs; two are discussed here and the third is discussed below under Hypothesis 3. First, the origin of the Apollo 16 MIMBs as Nectaris melt is inconsistent with available geochemical data. Apollo 16 MIMBs, particularly those of groups 1M and 1F, are rich in incompatible elements (8–9 μg/g Th; Table 2) and are the only significant carriers of Th in the Apollo 16 regolith (86%; Table 8). Yet, the distribution of Th in the Central Highlands increases from low values near the rim of Nectaris ($\leq$1 μg/g) to high values near Imbrium (>5 μg/g; Metzger *et al.*, 1981), and there is no evidence in the Apollo orbital gamma-ray data for Th-rich ejecta from Nectaris, as there is for Imbrium. Also, Mg/Al ratios generally increase from values typical of anorthosites to those typical of norites along a line from the Kant plateau (east of the Apollo 16 site, toward Nectaris) to Imbrium (Andre and El-Baz, 1981). Finally, at the Apollo 16 site, MIMB samples are more abundant in the Cayley Formation (surface regolith of central and southern Apollo 16 stations) than they are in the Descartes Formation (North Ray Crater ejecta). All of these observations are more consistent with Imbrium being the source of the MIMBs than Nectaris.

Second, there is the problem of the ancient regolith breccias. If the Apollo 16 MIMBs derive from the Nectaris basin, then the ancient regolith breccias cannot represent a pre-Nectaris regolith because the breccias contain a substantial component of MIMBs (mean: 27%; Korotev, 1996). Yet, from both petrographic (McKay *et al.*, 1986) and geochemical arguments (Korotev, 1996), the ancient regolith breccias appear to be binary mixtures of MIMB fragments and a fine-grained surface soil which itself is a mixture of a variety of mostly feldspathic lithologies; that is, the ancient regolith of the breccias seems to have formed by admixture of MIMBs to an even older feldspathic surface regolith, the Cayley prebasin regolith of Table 10, column 2. If the MIMB clasts are from Nectaris, then what ancient regolith do the regolith breccias represent? Unless the Nectaris ejecta consisted largely of MIMBs, which they did not (Th argument), the mixing of Nectaris ejecta and the ancient, feldspathic prebasin regolith should have substantially buried and diluted the prebasin regolith. Only an insignificant proportion of the Nectaris ejecta deposit could consist of pre-Nectaris regolith with the anomalously high $^{40}Ar/^{36}Ar$ characteristic of the ancient regolith breccias. Yet ancient regolith breccias are a relatively common component of the Cayley regolith. Hypothesis 1 cannot account for the ancient regolith breccias.

Hypothesis 2: Nectaris and Imbrium–The hypothesis that some Apollo 16 MIMBs derive from Imbrium and the rest from Nectaris (Spudis, 1984) stemmed naturally from the observation that there are two main compositional classes of MIMBs, group 1 ("LKFM," from Imbrium) and group 2 ("VHA," from Nectaris). The recognition of subgroups of groups 1 and 2, particularly the difference in Mg/Fe ratio between groups 1M and 1F and between groups 2DB and 2Mo (Korotev, 1994), detracts somewhat from the simplicity of the hypothesis and allows four or more basins to be accommodated as easily as two.

The main problem with Hypothesis 2 is that all Apollo 16 MIMB groups appear to derive from a common provenance geochemically. Although Apollo 16 MIMBs contain a KREEP component generally similar to that of MIMBs from other Apollo sites, in detail relative abundances of incompatible lithophile elements (*e.g.*, Th/REE ratios and REE "patterns") in groups 1M and 2DB, for example, are more similar to each other than they are to MIMBs from other sites (Palme, 1977; Korotev, 1994). Siderophile-element concentrations and ratios are also a serious impediment to any multiple-impact hypothesis. All Apollo 16 MIMB groups have a siderophile-element signature that is essentially unique to the site: an Ir/Au ratio at the low end of the range for lunar polymict samples (Hertogen *et al.*, 1977) coupled with high absolute abundances of all siderophile elements (see "Mafic Impact-Melt Breccias" and "Meteoritic Material" under "Lithologic Components...," above). Thus, any multiple-impact hypothesis requires that either (1) the unusual siderophile-element signature is a feature of the target area of all the impacts, emplaced by an earlier, larger impact, or (2) the multiple impactors that formed the Apollo 16 MIMBs were all related, metal-rich bolides (Korotev, 1987c). The second option, in particular, is improbable and the probabilities of both options decrease as the size of the area from which the breccias derive or the presumed number of impacts increase. Also, as noted above, there is no evidence in the orbital geochemical data that Nectaris ejected any substantial amount of material that is as mafic and rich in Th as the group-2 MIMBs. Thus, the hypothesis that is least in accord with the geochemical data is that the Apollo 16 MIMBs derive from two or more basin-forming impacts separated by distances such as that between Imbrium and Nectaris (~2100 km). Such a hypothesis would require a remarkable degree of geochemical similarity between widely spaced target areas as well as the coincidence that two or more basins were formed by similar, but unusual, impactors that resemble group IAB irons (James, 1996; Korotev, 1987c). For similar reasons, the hypothesis that some Apollo 16 MIMBs are from a basin and that others are from craters in the Central Highlands is also improbable.

Hypothesis 3: Local Craters–The hypothesis that the Apollo 16 MIMBs derive from several impacts that formed large (~100 km) craters in the Central Highlands is based mainly on the occurrence of different compositional groups (Ryder and Seymour, 1982; Reimold and Nieber-Reimold, 1984; Korotev, 1987c, 1991b). The hypothesis is supported by differences in apparent crystallization ages among samples (Reimold and Nieber-Reimold, 1984; Stöffler *et al.*, 1985), the existence (or possible existence; Spudis, 1984) of several old, possibly pre-Nectaris craters with diameters up to 150 km that occur in the vicinity of the site (Head, 1974), and models that suggest that most of the material of the Cayley plains is of local derivation (Morrison and Oberbeck, 1975). Thus, the simplest interpretation of the lithophile-element data, based on the observation that impact-melt breccias found within terrestrial craters are uniform in composition, is that the Apollo 16 MIMBs were produced by at least two, and possibly five or more, impacts into a single geochemical provenance such as the Central Highlands. The high and uniform relative abundance of MIMBs in the Cayley plains (Fig. 9) is consistent with an origin of the MIMBs either as Imbrium ejecta or as a major component of the pre-Imbrium surface material; in either scenario, the MIMBs would be well mixed in the megaregolith by the process that formed the Cayley plains. It is not consistent, however, with small post-Imbrium impacts that punched through layers of feldspathic Imbrium or Nectaris ejecta and excavated and mixed impact melt that had previously pooled in large pre-Imbrium or pre-Nectaris craters, because this mechanism cannot achieve the observed high concentration and uniform distribution of MIMBs in the surface regolith. (Consider, for example, the small degree of mare-highlands regolith mixing that has occurred at the Apollo 17 site since flooding of the valley or since deposition of the Light Mantle deposit; Fig. 6.) Thus, if the Apollo 16 MIMBs are from local craters, the MIMBs must have been a major component of the pre-Imbrium surface.

Numerous objections have been made to the local-crater hypothesis. First, the siderophile-element data still require a special circumstance, namely, that the several impactors that formed the craters either struck a region with a high abundance of Fe-Ni metal from a previous impact or were related metal-rich bolides (Korotev, 1987c, 1994). Second, the feldspathic upper crust of the Central Highlands is too thick for impacts that formed 50–150 km diameter craters to yield impact-melt breccias, such as groups 1M and 1F, that are as mafic as MIMBs from other sites that are believed to be basin melts (Spudis, 1984). If the Apollo 16 MIMBs are from 50–150 km diameter craters, then the melt zone must be within the upper ~20 km of the crust (*e.g.*, Warren *et al.*, 1996), and the upper feldspathic portion of the crust of the Central Highlands can, therefore, be only a few kilometers thick. Yet ejecta from Nectaris (a much bigger impact) appear to be largely feldspathic, and there is no indication in the results of Neumann *et al.* (1996) that crustal thickness in the region of the Apollo 16 site is in any way anomalous (*i.e.*, thin). Third, some (at least) of the candidate local craters (Dollonds B and C, Unnamed B) may be secondary craters, in which case they would not contain impact melt (Spudis, 1984; Wilhelms, 1987). Fourth, most impact melt is formed in basins (Grieve and Cintala, 1992; Cintala and Grieve, 1994; Warren *et al.*, 1996); thus from a probabilistic standpoint, it is unlikely that impact melt breccias that are derived from craters, as opposed to basins, could be so abundant at the site. Fifth, any melt that was produced in local pre-Nectaris craters should have been largely buried by Nectaris ejecta (Wilhelms, 1987).

To this list, one can add the problem of the ancient regolith breccias. The proportion of Apollo-16-type MIMB component in the regolith breccias (mean: 27%, Korotev, 1996, with an uncertainty of ±6%, 95% confidence based on Sm concentrations in 12 samples) is essentially the same as the proportion in the present soils (25 ± 2%; Table A2). This similarity suggests that the ancient regolith breccias were formed from post-Imbrium regolith. However, admixture of the Apollo-14-type component to the present regolith appears to postdate closure of the ancient regolith breccias. Thus, Hypothesis 3 requires that none of the MIMBs of the Cayley plains are Imbrium ejecta. If the ancient regolith breccias represent pre-Imbrium regolith instead, then the similarity in MIMB abundances between the breccias and the present soil indicates that the proportion of primary Imbrium ejecta at the site must be so low that there was no substantial dilution of the local components by Imbrium ejecta. As discussed in more detail next, both alternatives are unlikely and neither accounts for the observation discussed earlier that the ancient regolith breccias appear to represent a feldspathic surface regolith to which MIMB fragments were added.

The final barrier to any hypothesis that forms the Apollo 16 MIMBs outside the Imbrium region is the nature of Imbrium continuous ejecta deposits. Morrison and Oberbeck (1975) estimate that 13–18% of the deposits emplaced by Imbrium secondaries at the Apollo 16 site is primary Imbrium ejecta; the rest is pre-Imbrium substrate, which would include the MIMBs, if they derive from local craters or Nectaris. If the 25% component of Apollo-16-type MIMBs in the Cayley regolith are part of the pre-Imbrium substrate, then the Imbrium ejecta must consist almost entirely of feldspathic materials (*i.e.*, the prebasin components of Fig. 8; the mare components are probably post Imbrium), and the only reasonable candidate for Imbrium impact melt at the site is that 3.5% of the regolith (Model 1) that appears to be Apollo-14-type MIMB. Thus, both Hypotheses 1 (Nectaris) and 3 (local-craters) require selecting between two alternatives, neither of which is credible. (a) If primary Imbrium ejecta is, in fact, a substantial ingredient of the Cayley regolith (*e.g.*, 13–18%, or more), then that ejecta must consist entirely of the feldspathic prebasin components of Fig. 8 and, consequently, be more feldspathic and poorer in incompatible elements, on average, than is the Nectaris or local component, which would include the MIMBs. This alternative is not consistent with the orbital geochemical data or the observation that the abundance of MIMBs appears to decrease with depth at the site. (b) The Cayley plains at the Apollo 16 site contain only a few percent primary Imbrium ejecta, and no more than ~4% of the regolith (*i.e.*, the Apollo-14-MIMB component) is mafic KREEP-bearing material from the Imbrium region. This alternative necessitates that both the feldspathic materials and the Apollo-16-type MIMBs were pre-Imbrium components of the local regolith in approximately their present proportions and that the intimate mixing of the two types of components in the megaregolith must have occurred pre-Imbrium, presumably by Nectaris. Thus, the second alternative is essentially tantamount to saying that Nectaris, not Imbrium, was responsible for emplacement of the Cayley Formation.

Hypothesis 4: Imbrium–The remaining hypothesis, one suggested by Taylor and Marvin (1981) but which I do not believe has been previously advocated seriously, except indirectly by Evensen *et al.* (1974) and more recently by Haskin (1997a), is that all Apollo 16 MIMBs derive from the Imbrium region, where concentrations of Th and other incompatible elements are appropriately high (Arnold *et al.*, 1977; Metzger *et al.*, 1977). Hypothesis 4 is the one most consistent with the known distribution of Th on the lunar surface (Haskin, 1997a) and would easily account for the intimate mixture of MIMBs (Imbrium ejecta) and feldspathic materials (mostly local material) in the Cayley plains. It is also consistent with one small, but nonetheless tantalizing, observation: the occurrence of two small melt-breccia fragments at the Apollo 15 site (samples 15243, 40 and 15243,41; Ryder *et al.*, 1988) that are texturally and compositionally indistinguishable from Apollo 16 group 1M, including the uniquely low Ir/Au ratio characteristic of ancient meteorite group 1LL (Hertogen *et al.*, 1977; see also Fig. 21 of Korotev, 1994). Hypothesis 4 includes two extreme options: (a) the MIMBs derive from one or more pre-Imbrium craters in the Imbrium region and the Imbrium impact delivered them to the Apollo 16 site during formation of the Cayley plains as primary Imbrium ejecta or secondary crater ejecta or (b) all Apollo 16 MIMBs formed in the Imbrium impact itself and are primary ejecta.

Two main objections to an Imbrium origin of the Apollo 16 MIMBs (Hypotheses 4a or 4b) are that the hypothesis requires that (1) a large amount of material from the Imbrium region was delivered to a location that is almost three basin radii from the center of the basin (Fig. 11) and (2) most of that material was impact-melt breccia (Korotev, 1994). Neither objection is formidable, however, particularly when the unusual nature of the Imbrium event is considered. There is photogeologic evidence that long-distance transport of primary ejecta occurs (Schultz, 1981), and Wilhelms (1987; p. 212) notes that many of the parameters of the equation that led Morrison and Oberbeck (1975) to conclude that the maximum proportion of primary Imbrium ejecta at the site was only 18% are model dependent and uncertain. For example, the combined effect of a small change in the exponent of the scaling relation (H. J. Moore, cited in Fig. 10.26 of Wilhelms, 1987) combined with changing the ejection angle by 5° raises the upper limit from 18% to 39%. Both the ratio of melt volume to transient crater volume and the fraction of impact melt ejected from the transient crater increases with crater size (Schultz and Mendenhall; 1979; Warren *et al.*, 1996), and the recent estimates of Warren *et al.* (1996) allow for 25% or more of the Imbrium ejecta to be melt, so a high volume of ejected melt is not a impediment to Hypothesis 4b.

One point in favor of an Imbrium origin is the unique nature of the Imbrium-Procellarum region. It is likely that the region was geochemically anomalous prior to the Imbrium impact, that is, that feldspathic crust was essentially absent and the region was dominated by some form of KREEP basalt precursor (Cadogan, 1974; Haskin, 1997b; Korotev, 1997). This circumstance would account for one of the problems of Hypothesis 3 (local craters), namely, how such mafic melt could be produced by subbasin-sized craters. Melt breccias produced by even small pre-Imbrium impacts into such a region (Hawke and Head, 1977; Stadermann *et al.* 1991) would be mafic and rich in Th. Wilhelms (1987, p. 218) notes that the proportion of material at the Apollo 16 site that derives from the Imbrium region might be much greater than the maximum predicted by Morrison and Oberbeck (1975) if the debris surge that is believed to have formed the plains carried material from uprange (*i.e.*, if the deposits originated in part from secondary cratering to the northwest of the site). This consideration would be important if the Apollo 16 MIMBs derived from craters outside the Imbrium transient crater but still within the pre-Imbrium high-Th region (a possibility allowed under Hypothesis 4a). Because of the high KREEP abundance in the target area of the Imbrium impact, the area may have been unusually hot or even molten, thus leading to production of a larger-than-normal volume of impact melt (Spudis, 1984; Spudis *et al.*, 1984). Along the same line, there is the nature of the Imbrium impactor. If the Apollo 16 MIMBs were formed during the Imbrium impact, then the impactor was probably an iron meteorite (Korotev, 1987c; James, 1996), which would carry more energy than assumed in most models and produce more melt.

Arguments can be made for both Hypotheses 4a (pre-Imbrium craters) and 4b (Imbrium melt), although I believe the considerations below favor Hypothesis 4b. Hypothesis 4a is probably more consistent with the poikilitic texture of the group-1 MIMBs, a texture that suggests a stage of slow cooling (Simonds *et al.*, 1973). It is also consistent with the lithophile-element groupings, although, as noted earlier, the occurrence of different compositional groups is not a strong argument against Hypothesis 4b because there is no particular reason to believe that all impact melt ejected from an expanding basin cavity is identical in composition. Geochronologic data are scarce for Apollo 16 MIMBs, particularly for samples from the Cayley plains stations. Although reported ages among samples sometimes differ by amounts significant with respect to their analytical uncertainties, most samples that can be reasonably assigned to compositional groups 1 or 2 (adequate compositional data are often lacking, however) are consistent with an age of ~3.95 Ga (see summaries of Podosek, 1981; James, 1981; and Reimold and Nieber-Reimold, 1984). This is older than the presumed age of Imbrium (3.75 Ga, Stadermann *et al.*, 1991; ≤3.87 Ga, Dalrymple and Ryder, 1993). Thus, if the geochronologic data are interpreted to indicate that there are actual age differences among the Apollo 16 compositional groups, then Hypothesis 4a is in accord with that interpretation and the presumed age of Imbrium. Hypothesis 4b, in contrast, necessitates that the Imbrium basin formed ~3.95 Ga ago and that any apparent differences in ages among individual MIMB samples result from some effect that causes crystallization ages to be imprecisely recorded. Nevertheless, there are two main reasons to favor Hypothesis 4b over 4a. (1) Hypothesis 4b accounts for the siderophile elements in a straightforward manner: Imbrium was formed by the impact of an iron meteorite with an Ir/Au ratio ~0.3× that of chondrites. With Hypothesis 4a, the siderophile-element signature would have to derive from an older, larger basin (*e.g.*, Gargantuan or Procellarum; Cadogan, 1974; Wilhelms, 1987). (2) From arguments summarized above, the existence of 25% MIMBs in the regolith of the Cayley plains at the Apollo 16 site could be accommodated by Hypothesis 4b. Hypothesis 4a, in contrast, requires the somewhat improbable circumstance that although much of the Imbrium ejecta directed toward the Apollo 16 site was melt breccia, it was not melt breccia formed in the Imbrium impact. Where, then, is the Imbrium melt? This concern could be accommodated within Hypothesis 4a if the target area of the Imbrium impact contained a higher-than-normal proportion of impact-melt breccia as a result of the anomalous nature of the region (high-temperature).

If the Apollo 16 MIMBs were formed in the Imbrium region, the origin of MIMBs from other Apollo sites also comes into question (*e.g.*, Rockow and Haskin, 1996). The high relative abundances of normative components of KREEP basalt and troctolite, compared to feldspathic components, in MIMBs from all Apollo sites suggest that perhaps all KREEP-bearing MIMBs derive from the Imbrium-Procellarum region (Korotev, 1997). Although the relationship between the Apollo 16 MIMBs and MIMBs from other sites is beyond the scope of this paper, I conclude this section by addressing the issue of siderophile elements in this context. The unique siderophile-element signature of Apollo 16 MIMBs has been used to argue that they were produced in an impact distinct from those producing melt breccias from other sites (Hertogen *et al.*, 1977; Korotev, 1987c, 1994). By this argument, if Apollo 16 MIMBs were produced in the Imbrium impact, then none of the Apollo 15 MIMBs, which were collected on the basin rim, would represent Imbrium melt (except for the two 15243 particles discussed at the beginning of this section). However, recent reevaluations of the siderophile-element data (James, 1995, 1996) show that siderophile-element ratios in the Apollo 16 MIMBs (which resemble those of group IAB irons; James, 1996) are more similar to those of MIMBs from Apollos 14 and 15 than advocated by Korotev (1994) and that some of the differences in intersite siderophile-element ratios in MIMBs are probably clast effects (L. Haskin, pers. comm.). Although this area requires more study, preliminary work suggests that most of the variation in Ir/Au ratios observed in Apollo MIMBs could be accommodated by two classes of meteoritic components: (1) low-Ir/Au, Fe-Ni metal (the Imbrium projectile?), which is at high abundance in Apollo 16 MIMBs and lower abundance in MIMBs from other sites, and (2) other components, perhaps clastic (pre-Imbrium breccias?), with more nearly chondritic Ir/Au ratios.

In summary, worthy objections can be raised to any explanation for the origin of the Apollo 16 mafic impact-melt breccias and the favoring of any one scenario involves selecting which set of arguments seems most compelling and finding fault with the others. Persons of different backgrounds are compelled by different sets of arguments. In that context, from the perspective of regolith composition and the assumption that the Cayley plains are primarily an ejecta deposit from Imbrium, I favor Hypothesis 4. The uniform distribution of KREEP-bearing MIMBs in the Apollo 16 regolith coupled with the known distribution of Th on the lunar surface from the Apollo orbiting gamma-ray experiments is consistent only with origin of the mafic melt breccias from the Th-rich region where the Imbrium basin now lies.

HISTORY OF THE APOLLO 16 REGOLITH

The observations and results I review and report here, which are based largely on studies of the Apollo 16 samples, lead me to the following model for the history of the Apollo 16 regolith. The scenario described differs in some details from previously proposed models. Prior to the Nectaris impact, the surface of the Central Highlands consisted of highly feldspathic material with ~31–32% Al_2O_3, on average. The Nectaris impact had a significant effect on the site topography, as argued by Stöffler *et al.* (1985) and Spudis *et al.* (1989), but the impact did not substantially change the surface composition of the region. This conclusion is based largely on the compositional similarity of the estimated "prebasin components" of the Descartes Formation, as inferred from feldspathic fragmental breccias of North Ray Crater, and those of the Cayley Formation, as inferred from the ancient regolith breccias (Korotev, 1996), as well as their mutual similarity to the inferred composition of Nectaris basin ejecta near the site based on orbital data (*e.g.*, Table 1 of Spudis *et al.*, 1989). An alternative possibility also allowed by the data is that highly feldspathic ferroan anorthosite (35% Al_2O_3) was the predominant lithology of the pre-Nectaris crust and the Nectaris impact contributed the noritic anorthosites, thus, lowering the average Al_2O_3 concentration to 31–32%. KREEP-rich mafic impact-melt breccia ("VHA" or "LKFM basalt"), however, was not a component of the Nectaris ejecta.

The Cayley plains are a continuous deposit formed by the Imbrium impact and possibly modified by Orientale. Primary Imbrium ejecta at the site includes, at least, that 25% of the Cayley regolith that is mafic impact-melt breccias of Apollo 16 groups 1 and 2. Some of the feldspathic materials may also be Imbrium ejecta (certainly, for example, the anorthosite in the dimict breccias), so the total proportion of Imbrium ejecta at the site may be much higher than 25%. The Apollo 16 MIMBs were probably formed during the impact of a metal-rich, possibly iron meteorite that produced the Imbrium basin, but they might be from one or more pre-Imbrium craters in or near the Imbrium excavation cavity. Some of the feldspathic material of the regolith is probably secondary ejecta from uprange of the site and the rest (most?) is local material of the Descartes Formation. The relative proportions of these various possible sources of feldspathic material are difficult to assess because of the similarity of feldspathic materials from different parts of the Moon and the lack of any systematic petrographic study comparing the feldspathic lithologies of the Cayley plains with those of North Ray Crater.

The mechanism of emplacement of mafic impact-melt breccias at the Apollo 16 site was sufficiently chaotic in time and space that North Ray Crater later sampled, at depth, feldspathic material containing primarily one type of melt breccia (group 2NR), while South Ray Crater sampled material dominated by another (group 2DB). However, the delivery was sufficiently homogeneous at the kilometer scale that samples of mature (*i.e.*, well-mixed) surface soil from anywhere at the site are all similar in composition. Of the feldspathic fragmental breccias of North Ray Crater, those that contain MIMB clasts are, thus, part of the Imbrium continuous ejecta deposit, although the feldspathic material itself may be from the Descartes Formation (Stöffler *et al.*, 1985). The assembly of the components of the feldspathic fragmental breccias occurred during the Imbrium impact by incorporation of MIMB clasts, some of submillimeter size, into fragmented feldspathic material with negligible surface exposure. The ancient regolith breccias formed similarly but with feldspathic near-surface regolith and a different population of mafic melt breccias, which is consistent with the hypothesis of McKay *et al.* (1986) that the two types of breccia formed in different zones of a megaregolith. The ancient regolith breccias probably represent post-Imbrium regolith in the vicinity of the site, although it is not clear whether the feldspathic fragmental breccias and ancient regolith breccias were lithified by the Imbrium event itself or by post-Imbrium crater-forming impacts. Various post-Imbrium impacts, possibly including the Orientale impact, have added some exotic materials to the regolith and excavated material from depth so as to change the regolith composition somewhat from that represented by the ancient regolith breccias. These materials include those of mare affinity, some combination of Apollo-16-type MIMB and anorthosite (dimict breccia?), and material of Apollo 14 affinity. The constancy of the abundance of mare-derived material in mature surface soils of the Cayley plains suggests that most of it was added as fine-grained material (pyroclastics and small impact glasses) not mainly as blocks of crystalline mare basalt from impacts into nearby maria.

SUMMARY AND CONCLUSIONS

A first-order and model-independent observation is that all mature soils from the Apollo 16 site are similar to each other in composition, and mature soils from the central portion of the site are similar in composition to mature soils from the southern portion of the site, 4 km away. Both regions are surfaced by materials of the Cayley plains. The lithologic components of the regolith, however, are highly diverse in composition. Thus, the megaregolith of the Cayley plains must have been well mixed on a kilometer scale prior to development of the present surface regolith. This conclusion is supported by the first-order compositional similarity of the present regolith to the ancient regolith breccias, which probably represent early postbasin regolith at or near the site.

Models presented here account for the composition of mature soil from the Cayley plains at the Apollo 16 site in terms of mixtures of lithologies that are observed to occur in the regolith as lithic fragments and rocks. The models use components representing primary and secondary lithologies such as, igneous rocks, impact-melt breccias, and granulitic breccias but not tertiary lithologies, such as agglutinates, regolith breccias, and glassy breccias. Although the number of possible combinations of components that account reasonably well for the mass balance of the soil is large, the modeling was designed to explore all possible combinations and seek systematic results among the best model solutions. Conclusions stated below are based on average results for the best model solutions.

The regolith of the Cayley plains consists of ~64% prebasin surface materials, that is, lithologies that existed at or near the surface of the Moon ~4.0 Ga ago and their brecciated derivatives. About 29% of the regolith consists of KREEP-bearing mafic impact-melt breccias ("VHA" and "LKFM") created at the time of basin formation (~3.9 Ga). Another 6% is mare-derived material (*i.e.*, impact glasses, pyroclastic glasses, and crystalline mare basalt). Finally, there is 1% meteoritic material (modeled as volatile-free CI chondrite) in excess of that carried by the breccias of which the soil is largely composed.

With average concentrations of ~31–32% Al_2O_3 and 2–3% FeO, the prebasin materials are highly feldspathic (90% normative plagioclase). These materials are now represented by cataclastic anorthosite and noritic anorthosite, granulitic breccias, fragmental breccias, impact-melt breccias, nonmare mafic lithologies, and glasses. On average, the prebasin components of the regolith of the Cayley plains are similar in composition to the feldspathic lunar meteorites but are more aluminous because of a particularly high abundance at the Apollo 16 site of ferroan anorthosite consisting almost entirely of plagioclase. On average, the Mg/Fe ratio of these prebasin components is at the high end of the range observed in ferroan anorthosites (Mg' = 68). The principal high-Mg/Fe component of the regolith is granulitic breccia of noritic- and troctolitic-anorthositic composition (and, probably, fragmental breccias derived in part from granulitic breccias or their precursors). Model results suggest that gabbronorites (in excess of any gabbronorite component of the breccias) may be as abundant as 4% of the prebasin component (*i.e.*, 2.6% of the present total). If regolith such as that represented by the Apollo 16 ancient regolith breccias is a protolith of the present regolith of the Cayley plains (McKay *et al.*, 1986), then the present regolith consists of at most 71 ± 5% of this ancient regolith, with the remainder being mare-derived material and a combination of mafic impact-melt breccia and anorthosite.

On average, the requirement for mare-derived material (specifically, an excess in the soil of Sc and related elements) is satisfied by a basalt component with an average TiO_2 concentration of ~2.4%. Taken at face value, the model results indicate that the mature regolith of the Cayley plains contains 98% of the Na in the best-fit combination of rock components that accounts for other lithophile elements; the rest was presumably lost by volatilization during micrometeorite impacts.

Mafic impact-melt breccias are the principal carriers of siderophile elements (*e.g.*, 56% of the Ni) and incompatible trace elements (80–86% of the REE and Th) in the regolith of the Cayley plains. Elements associated with mafic phases are carried largely by the mafic impact-melt breccias (40–50%), but a significant portion is also carried by the mare-derived components (15–30%). In total, only 29% of the Fe in mature soil from the Cayley plains is from prebasin (early crustal) components; the majority derives from syn and postbasin "contamination" (mare-derived material, postbasin meteoritic material, and mafic impact-melt breccias).

There is compositional evidence that some Th-rich lithology such as that occurring at the Apollo 14 site is also a component of the Cayley plains. Mass balance for several elements, particularly Th, is improved significantly by inclusion of 3.5% of a component of Apollo-14 melt breccia. This component appears to have been added to the regolith after closure of the ancient regolith breccias. At least one melt breccia particle of apparent Apollo 14 affinity was found among 1–2 mm soil particles analyzed here.

The abundance of KREEP-bearing, mafic impact-melt breccias in mature regolith samples from the Cayley plains at the Apollo 16 site is both high and relatively constant (25–32%, range among sampling stations). This observation provides an important boundary condition for models of formation of the plains and derivation of the melt breccias. Based on this and other constraints (primarily, the known distribution of Th on the lunar surface), it is unlikely that any of the mafic impact-melt breccias of Apollo 16 derive from large local craters or from Nectaris. Most probably, despite the compositional variation, they are breccias of impact melt produced in the Imbrium region. The high abundance of Imbrium ejecta in the form of melt breccia at the Apollo 16 site is probably related to unusual chemical and physical properties of the target area (high Th, possibly high target temperature) as well as an unusual impactor (iron). Tests of this hypothesis could be provided by (1) a systematic geochemical and petrographic study of small lithic fragments of the Cayley plains, with comparison to samples of North Ray crater ejecta, (2) a systematic study of crystallization ages of Apollo 16 mafic impact-melt breccias, such as those of Dalrymple and Ryder (1993, 1996) for other sites, and (3) a global map of the distribution of Th on the lunar surface.

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APPENDIX

Mathematics

The mathematics of the least-squares calculations are described in detail in Korotev *et al.* (1995) and summarized here. The estimated (model) concentration of element i (*e.g.*, Table A1, columns 1–4) in the MCS (mature Cayley soil) composition was calculated from the mass-balance equation

$$Y_i = \sum_{j=1,m} y_{i,j} f_j \qquad \text{Eq. (1)}$$

where $y_{i,j}$ is the concentration of element i in component j (*e.g.*, Table 2), f_j is the mass fraction of component j, and m is the number of components (m = 6, 7, 8, or 9 in Model 1, m = 5, 6, 7, or 8 in Model 2). For each assumed combination of components in each model calculation (*e.g.*, Table A2, columns 1 or 2), the best-fit solution (the set of values f_j) was obtained by minimizing the expression

$$\chi^2 = \sum_{i=1,n} w_i (C_i - Y_i)^2 \qquad \text{Eq. (2)}$$

where C_i is the observed concentration of element i in the MCS composition (Table A1, column 5), w_i is a weighting factor ($w_i = \sigma_i^{-2}$; Table A1, column 8), and n is the number of elements (Model 1: n = 17; Model 2: n = 16, *i.e.*, Na excluded). Reduced χ^2, the goodness of fit parameter, is given by χ^2/ν, where $\nu = n - m$.

Model 1

Components--Except for the CI-chondrite component, each of the model components falls into one of three compositional "supercomponents" that correspond (with some overlap) to the three "element associations" discussed in the text: (1) feldspathic, (2) mafic igneous, and (3) mafic, KREEP-bearing impact-melt breccias (MIMBs). Each supercomponent comprises several discrete components, each of which represents a lithology. For some nominal lithologies that have a large range of compositions, two or more components representing the compositional extremes were included in the model. As a convenience here, I use acronyms (*e.g.*, NAn, MIMB-16) to refer to model components.

The feldspathic supercomponent includes nine discrete components falling into two categories. One category consists only of highly feldspathic ferroan anorthosite (FAn: ~99% plagioclase), the other consists of eight components I collectively designate "noritic anorthosites" (NAn: 77–88% normative plagioclase, by mass), although the magnesian granulitic breccia component (GrB-Mg) has the normative composition of a troctolitic anorthosite. The NAn components are all similar in composition (*e.g.*, 27–31% Al_2O_3; Table 2) and include both breccias and ferroan-anorthositic-suite plutonic rocks. Nearly any generic Apollo 16 "anorthosite" is compositionally equivalent to a mixture of these nine components. No component of anorthositic norite composition (19–26% Al_2O_3) is included in the model explicitly. Most plutonic ferroan anorthositic norites are sufficiently small that they are probably unrepresentative fragments of more feldspathic rocks (Haskin and Lindstrom, 1988). The largest Apollo 16 anorthositic norite, sample 67215, is classified as a ferroan granulitic breccia by Lindstrom and Lindstrom (1986) and it is one of five samples I used to obtain the composition of the corresponding GrB-Fe component (Table 2).

In total, the model includes 16 mafic igneous components that also fall into two categories, mare-derived components and nonmare, mafic plutonic components. The ten mare-derived components cover most of the compositional range of known mare basalts and pyroclastic glasses. They include: (1, 2) Apollo 11 low-K and high-K, (3) Apollo 14 aluminous group 5, (4, 5) Apollo 15 olivine and quartz normative, (6) Apollo 17 high-Ti, (7) Luna 16 aluminous, (8) Luna 24 very-low-Ti, (9) Apollo 15 green glass, and (10) Apollo 17 orange glass. (See Taylor *et al.*, 1991 for a discussion of these basalt types. Because these are minor components, their compositions are not listed here, but see Taylor *et al.*, 1991 and Haskin and Warren, 1991 for typical compositions.) The six nonmare mafic plutonic components represent (11, FGN) a ferroan-anorthositic-suite gabbronorite, sample 67513,7012 (Jolliff and Haskin, 1995) and all of the pristine Mg-suite samples observed at Apollo 16 for which there are adequate compositional data: (12, EG) eucritic gabbro 61224,6 (Marvin and Warren, 1980); (13, FL) feldspathic lherzolite 67667 (Warren and Wasson, 1979a); (14, SFG) the sodic ferrogabbro from 67915 (Marti *et al.*, 1983); (15, AGN) the alkali gabbronorite from 67975 (James *et al.*, 1987); and (16, ST) spinel troctolite 67435,77 of Ma *et al.* (1981). Of the six nonmare mafic components, five are gabbronorites (*Mg'*: 31–73); only the spinel troctolite is highly magnesian (*Mg'* = 91).

TABLE A1. Best, worst, and average fits for excellent solutions from Models 1 and 2.

	Composition								Error-wt'd. residuals	
	Y_i				C_i	$Y_{i,\,\mathrm{mean}}$		σ_i	$(Y_{i,\,\mathrm{mean}}-C_i)/\sigma_i$	
Model:	1		2		MCS	1	2	1	1	2
	worst	best	worst	best		$N = 682$	$N = 43$			
Note:	1	2	3	4	5	6	7	8	9	10
TiO_2	0.597	0.595	0.586	0.595	0.595	0.594	0.596	0.015	–0.09	0.09
Al_2O_3	26.9	26.8	26.6	26.7	26.7	26.8	26.7	0.3	0.23	–0.04
FeO	5.58	5.49	5.60	5.54	5.51	5.51	5.57	0.06	0.04	1.15
MgO	6.10	6.14	6.20	6.14	6.14	6.12	6.17	0.06	–0.33	0.55
CaO	15.25	15.28	15.34	15.36	15.30	15.28	15.37	0.15	–0.13	0.48
Na_2O	0.448	0.463	0.489	0.481	0.457	0.467	0.481	0.011	0.87	*4.52*
Sc	9.58	9.66	9.67	9.65	9.64	9.63	9.65	0.10	–0.07	0.10
Cr	777	775	775	772	775	775	772	8	–0.03	–0.44
Co	31.5	31.7	32.0	31.6	31.7	31.6	31.9	0.3	–0.39	0.59
Ni	464	452	469	457	454	460	457	11	0.51	0.25
Ba	146	147	143	144	146	145	144	4	–0.23	–0.59
La	13.37	13.31	13.47	13.53	13.30	13.35	13.46	0.13	0.36	1.24
Sm	6.23	6.17	6.13	6.17	6.18	6.19	6.14	0.06	0.12	–0.59
Eu	1.198	1.195	1.201	1.193	1.200	1.195	1.191	0.012	–0.40	–0.76
Yb	4.38	4.39	4.30	4.33	4.37	4.39	4.32	0.04	0.47	–1.03
Lu	0.600	0.606	0.602	0.607	0.608	0.603	0.605	0.006	–0.81	–0.47
Th	2.19	2.19	2.20	2.23	2.22	2.21	2.23	0.06	–0.27	0.16
Mg'	66.1	66.6	66.4	66.4	66.5	66.4	66.4	—	—	—
χ^2/ν	1.00	0.19	0.97	0.58	—	0.62	0.80	—	—	—

Oxides values and *Mg'* in percent, others in μg/g (*Mg'* shown for information only; not used explicitly in fitting). For this analysis, all combinations of the MIMB16 or NAn components for which the minimum χ^2/ν exceeded 1.00 were discarded (see text). Mean results for the remaining "excellent" solutions are given in columns 6–7, with the error-weighted residuals for the means given in columns 9–10. Among excellent solutions, the worst and best fits are also presented (columns 1–4). These compositions correspond to sets of components in the like-named columns of Table A2.

The MIMB components also fall into two categories: Apollo-14-type breccias (MIMB14), represented by a single component, and Apollo-16-type breccias (MIMB16), represented by four of the compositional groups of Korotev (1994), 1M, 1F, 2DB, and 2Mo (Table 2). Other Apollo 16 MIMB groups are either very similar in composition to one of the four MIMB16 components (2NR) or are mathematically redundant (2M, 2F) in that their compositions correspond to mixtures of the MIMB16 components and the nine feldspathic components.

Elements–I obtained the composition of each component by selecting as many representative samples of the corresponding lithologies as possible and averaging data for the samples. For the nonmare mafic components, however, there is usually only one well-analyzed sample of each lithology. The chemical elements modeled are those listed in Tables 2 and A1. Although not an exhaustive list, experience shows that if mass balance can be achieved for these 17 elements (*e.g.*, Stöffler *et al.*, 1985), mass balance for other lithophile elements is also satisfied because of interelement correlations among the trace elements. Data for SiO_2 would have provided a useful constraint but reliable data are not available for many of the components. As at other sites, the modeling was done with a weighted least-squares technique (Boynton *et al.*, 1975; Korotev *et al.*, 1995). Because all of the elements used are key elements that are determined with high or moderately high precision, most of them were given the same relative weighting factor in the fitting procedure: σ_i in Table A1 is 1% of the concentration value. A few elements were weighted less heavily (2.5%) because their relative abundances are determined less precisely (Ti, Ni, Ba, and Th) or there is evidence that mass balance is not preserved (Na, see text).

Modeling Technique–Preliminary modeling showed that because of the large number of possible components and the similarity in compositions of many of them, the number of possible combinations of components that provided excellent fits was large; that is, there was no unique solution and many excellent solutions. Also, if the number of components exceeded about eight, solutions were often mathematically excellent but geologically unrealistic (*e.g.*, best-fit proportions of some components were <0% or >100%). Thus, in order to obtain useful results, I applied two techniques not usually used in modeling of this type. First, for two of the major classes of components, the NAn and MIMB16 components, I calculated a set of compositions representing mixtures of the various specific components that incrementally covered the range of likely variation. For each least-squares model calculation, only one NAn and one MIMB16 composition was included, but each represented some preset mixture. Second, all possible combinations of premixed NAn and MIMB16 pairs were tested.

The MIMB components provide an example. Preliminary modeling showed that, for reasons discussed in the text, if two or more of the MIMB16 components were included in the model at the same time and their abundances were allowed to be free parameters, best-fit solutions were often unrealistic (*e.g.*, +45% group 1F and –25% group 2DB). Also, the model-predicted ratio of group-1 to group-2 MIMBs, for example, was highly dependent upon which specific components were chosen to represent the noritic anorthosite and mafic igneous supercomponents. In order to make a sensible compromise between minimizing the number of assumptions and mathematical components and testing all reasonable possibilities in a systematic and unconstrained manner, I treated the MIMB16 components in the following manner. I used a single composition, designated MIMB16-1, to represent the group-1 impact-melt breccias; the composition was calculated as a 76:24 mixture of groups 1F and 1M. This ratio is the average of that observed both among rock samples (72:28, in 21 samples studied by Korotev, 1994) and the 1–2 mm soil particles from the Cayley plains (80:20, in 77 group-1 particles of Fig. 5). Groups 1F and 1M are similar in composition and differ mainly in Al and Ca concentrations and Mg/Fe and Cr/Sc ratios. The group-2 impact-melt breccias were also represented by a single composition, MIMB16-2, calculated as a 95:5 mixture of group 2DB and 2Mo; again, this ratio is consistent with data for rocks and soil particles. (Group 2Mo is compositionally equivalent to a mixture of group 2DB and troctolite; Korotev, 1994.)

The most consequential ratio is $f_{2/(1+2)}$, that is, MIMB-2/(MIMB-1 + MIMB-2), because of the factor-of-two difference in concentrations of incompatible elements between groups 1 and 2 (Table 2). Data for rocks in the regolith suggest that $f_{2/(1+2)}$ is in the range of 70–80% (*i.e.*, that group 2 dominates). For example, of the ~67 crystalline, mafic impact-melt breccias (including dimict breccias) from the Cayley plains of Ryder and Norman (1980) for which there are compositional data, 73% are of group-2 composition (based on Sm concentration). Similarly, of the 77 soil particles of group-1 and group-2 composition (*i.e.*, 8–32 μg/g Sm) in Fig. 5, 81% correspond to group 2 (8–16 μg/g Sm). Thus, I tested a total of five MIMB16 supercomponents that bracketed the range. Specifically, the five MIMB16 components represented $f_{2/(1+2)}$ ratios of 50%, 60%, 70%, 80%, and 90%. In any given least-squares calculation, only one of the five MIMB16 supercomponents was included. This preset-mixture approach allows for the solutions with variable MIMB-1/MIMB-2 ratios but within observed limits.

TABLE A2a. Summary of results for excellent solutions from mass-balance Model 1: Mathematical components.

Column:	worst 1	best 2	mean 3	s.d. 4
MIMB16	24.8	25.7	25.3	2.2
MIMB14	4.7	3.1	3.5	0.9
NAn	33.3	28.1	31.4	8.7
FAn	27.5	33.5	30.4	6.8
Nonmare mafic 1	0.9	2.0	1.9	1.4
Nonmare mafic 2	1.1	0.6	0.7	0.6
Mare-derived 1	3.0	4.8	3.4	1.5
Mare-derived 2	3.6	2.0	2.6	0.9
CI chondrite	1.0	0.9	1.0	0.2
Σ	99.9	100.6	100.3	0.3
χ^2/ν	1.00	0.18	0.62	

Values in mass percent (except χ^2/ν, which is unitless). For the MIMB16 and NAn supercomponents, the various specific components were premixed at selected ratios; see text and Table A2b. Among 2520 MIMB16-NAn combinations, the combinations giving the single best and worst mathematical fits (minimum χ^2/ν) are shown, after excluding all combinations for which the minimum χ^2/ν exceeded 1. Also shown are the average and sample standard deviation (s.d.) for all solutions that yielded excellent solutions (*i.e.*, all for which the minimum χ^2/ν was ≤ 1; $N = 682$). Columns 3 and 4 are taken here to represent the best overall results of the model and are the same values as those of Table 6.

Because the eight NAn components are so similar to each other in composition (Table 2), they cannot all be included simultaneously in the least-squares calculations. There are no data available on the relative importance of the NAn components in the Cayley regolith, yet any assumptions about their relative abundance have strong effects on results for other components. So, as with the MIMB16 components, I used a single NAn supercomponent in each least-squares calculation, and the composition of that component was calculated as a preset mixture of the eight specific components. In total, 504 different NAn compositions were tested representing all possible combinations of the eight components taken three at a time in ratios 80:10:10, 60:20:20, and 40:40:20. Thus, any specific NAn component (*e.g.*, FIMB-3) could occur at 0%, 10%, 20%, 40%, 60%, or 80% of the total NAn component. All model calculations included one of the NAn premixed compositions and the FAn component, so the NAn/FAn ratio was not constrained.

The mafic igneous components (volumetrically minor) were not premixed but were treated as free parameters, except that no more than four such components were included at a time.

For each least-squares calculation, five to nine mathematical components were used: (1) one of the five premixed MIMB16 components, (2) the MIMB14 component, (3) one of the 504 premixed NAn components, (4) the FAn (ferroan anorthosite) component (Table 2), (5) a volatile-free CI-chondrite component (Korotev and Kremser, 1992), and (6–9) up to 4 of the 16 mafic igneous components. All possible combinations of MIMB16 and NAn components ($N = 5 \times 504 = 2520$) were tested. For each MIMB16-NAn pair, all possible combinations of the ten mare-derived components taken zero, one, or two at a time ($N = 56$) and all possible combinations of the six nonmare mafic components taken zero, one, or two at a time ($N = 22$) were tested for a total of 1232 (56×22) different combinations of mafic igneous components. Any solution requiring a negative abundance of any of the mafic igneous components was discarded and among the remaining solutions for any MIMB-NAn pair, all but the single best-fit (minimum χ^2/ν, below) combination of the mafic igneous components was also discarded. In other words, for any given MIMB16-NAn pair, some combinations of the mafic igneous components gave better fits than others, and only the single combination providing the best fit was considered further. In this way, the model "choice" of major components (some combination of MIMB16 and NAn) was not affected by an arbitrary assumption about the relative importance of the minor (mafic igneous) components; whichever set of mafic igneous components worked best with a particular MIMB16-NAn pair was the set that was used (this included none, if none provided a better fit than some). The only constraint imposed was that because the mafic igneous components were minor components, not more than two mare-derived and two nonmare mafic components were used at a time. In total, least-squares solutions were calculated for 3.1×10^6 different combinations of components (2520×1232) and the 2520 best solutions representing each MIMB16-NAn pair were analyzed for goodness of fit.

TABLE A2b. Summary of results for excellent solutions from mass-balance Model 1: Premixed and minor components.

Column:	worst 1	best 2	mean 3	s.d. 4
MIMB16	*24.8*	*25.7*	*25.3*	*2.2*
1F	1.9	3.9	4.5	2.2
1M	0.6	1.2	1.4	0.7
2DB	21.2	19.6	18.5	4.3
2Mo	1.1	1.0	1.0	0.2
$f_{2/(1+2)}$	0.90	0.80	0.76	0.13
Noritic anorthosite (NAn)	*33.3*	*28.1*	*31.4*	*8.7*
FNAn-C	13.3		2.4	4.3
FNAn-D		5.6	2.1	4.6
FFB-Fe			1.6	3.4
FFB-Mg	13.3	5.6	7.6	9.4
GrB-Fe			1.1	2.5
GrB-Mg		16.9	9.7	8.2
FIMB-3	6.7		3.1	6.6
FIMB-4			3.8	6.9
Nonmare mafic plutonic	*1.9*	*2.5*	*2.6*	*1.5*
EG			0.7	0.9
FL			0.6	1.7
SFG	0.9	2.0	1.0	0.8
AGN		0.6	0.1	0.2
FGN			0.1	0.4
ST	1.1		0.1	0.2
Mare-derived	*6.6*	*6.8*	*6.0*	*1.4*
A11 HiK			0.0	0.2
A11 LoK			0.2	0.4
A14 A15			0.2	0.8
A15 GGA	3.0	4.8	3.5	1.8
A15 ON			0.1	0.4
A15 QN			0.0	0.2
A17 HTi			0.0	0.1
A17 OG			0.1	0.3
L16 Al	3.6	2.0	1.9	1.0
L24 VLT			0.0	0.0

See Table 6 for component names and footnote to Table A1a. $f_{2/(1+2)} = (f_{2DB} + f_{2Mo})/f_{MIMB16}$.

Goodness of Fit–The solution of a least-squares calculation is the set of mass fractions (f_j) for the set of assumed components that gives the best fit to the average composition of mature Cayley soil. An "excellent" solution is defined here as one for which the goodness-of-fit parameter, χ^2/ν, is <1 (Korotev *et al.*, 1995). This stringent definition means that, on average (root mean square), observed and estimated concentrations agree within the weighting parameter σ_i (*i.e.*, 1% for most elements and 2.5% for Ti, Na, Ni, Ba, and Th, Table A1). MIMB16-NAn pairs for which χ^2/ν exceeded unity were not considered further. For illustration, the mathematically best and worst of the excellent solutions are presented in Tables A1 and A2. Note that the worst of the excellent solutions is not significantly worse than the best of the excellent solutions when the magnitude of the weighting factors is taken into account. Thus, I regarded all excellent solutions as equally good and take the average results of all 682 excellent solutions

$$\sum_{k=1,682} \frac{f_{j,k}}{682}$$

to be the best estimate of the relative proportions of the various components (summarized in Table 6, with details in Tables A1 and A2). The corresponding standard deviation is as a measure of confidence that a given component represents a volumetrically significant lithology of the regolith. For example, ferroan anorthosite was required for all excellent solutions in abundances (f_{FAn}) that averaged 36% with a standard deviation of 7%; thus, ferroan anorthosite is a volumetrically important component. On the other hand, spinel troctolite was used in only 112 excellent solutions ($f_{ST} = 0.2$–1.2%) and, consequently, not used as one of the two nonmare igneous components in 570 excellent solutions ($f_{ST} = 0$), for a mean and standard deviation of 0.08 ± 0.20%. Thus, a component of spinel troctolite is clearly not required for mass balance in the Apollo 16 regolith.

Excellent mathematical fits were obtained with all five tested values of $f_{2/(1+2)}$, but the best results (lowest mean χ^2/ν among excellent solutions) were obtained with $f_{2/(1+2)} = 80\%$, which is in agreement the sample data; the worst results were obtained with $f_{2/(1+2)} = 50\%$.

Model 2

Conceptually, Model 2 is like Model 1 with the following exceptions. First, I replaced the eight NAn components with a single ARB component that represents the average composition of the ancient regolith breccias (Table 2); the FAn component was retained as a discrete component. Second, I did not include any of the nonmare igneous components, implicitly assuming that, like the NAn components, these were carried by the ARB component. Third, so as not to make any assumptions about the nature of the apparent excess MIMB component (*i.e.*, the excess above that which was carried by the ancient regolith breccias), six different MIMB16 components were tested one at a time, thus representing the entire range of possible proportions (*i.e.*, $f_{2/(1+2)}$ = 1.0, 0.8, 0.6, 0.4, 0.2, and 0) of the MIMB-2 and MIMB-1 components. Fourth, all combinations of 0, 1, 2 or 3 of the ten mare-derived components were tested (instead of 0, 1, or 2, as in Model 1), for a total of 179 combinations. Finally, preliminary results showed that Na concentrations were consistently overestimated by 4–6% (relative). Suspecting that this might be related to loss of Na in mature soil, Na concentrations were eliminated as a constraint in the model. In total, 35 excellent solutions were obtained from a total of 1074 (6 × 179) possible combinations of MIMB16 and mare-derived components; average results are summarized in Tables 9 and A1. If the MIMB14 component is excluded, the lowest value of χ^2/ν obtained is 1.48; that is, no excellent solutions are obtained. Likewise, the FAn component is essential for mass balance.

In Model 2, excellent solutions were obtained from all tested values of $f_{2/(1+2)}$ with no favored value. As a consequence, the average value in Table 9 (51%) is intermediate to the range of tested values (0–100%) and has a large uncertainty (±35%), that is, mass-balance constraints cannot identify whether the apparent excess MIMB component of the present regolith is dominated by a particular type, compositional group, of Apollo 16 MIMB; it may be dominated by a single MIMB type.